Abstract

Substation refurbishment planning was traditionally initiated by deteriorated network performance indices and the physical observed state of the network. However, it can also be too late, resulting in deteriorated customer service and unnecessary company risk.

A Plant Health Index is developed, to understand and assess the condition of equipment during its life cycle. The plant health index will also be the input required when modeling failure prediction.

Distribution networks constitute the majority of installed electrical equipment when compared to transmission and generation networks.

Increased failure of aging systems is likely, as equipment which has traditionally been “idling”, is suddenly expected to operate close to 100% capacity.

Introduction

A Plant Health Index (PHI) is very much like a cholesterol or GP visit. It serves as an indication that impending failure or ill-health condition exists, so that the desired preventive measure can be taken. Thus, the question remains what are the indicators of the equipment condition or assets that will indicate how the equipment is able to provided the intended function for the intended period.

The scope of the thesis is focused on the Distribution substations with primary operating voltage equal to or less than 132kV and secondary voltage no less than 11kV, with an installed capacity greater than 1MVA. At this time, only power plant is considered as part of the study.

Currently, a proposal is being prepared to measure the reliability of large power transformers [1].

Reliability

Fig. 1 illustrates that if we know the condition; we can extract more out of the equipment, and are positioned to time the replacement at a point in the life cycle just before intolerable risk.

Beyond the intended investment period of 25 years, a revised maintenance strategy or intervention can be applied to preserve the equipment performance. In the case of transformers, more frequent samples of insulating oil in order to investigate sources of sudden deteriorated health, and moisture extraction are justified in order to establish possible causes of thermal faults. Typical “life extension” interventions for transformers include filtering or regeneration of the main tank oil, partial re-winding or bushing replacement.

Often circuit breakers need to be serviced more frequently for deteriorated performance of overhead line (frequency of faults). The effects include reduced dielectric strength during arcing, increased wear of finger contact and fatigue of the circuit breaker mechanism. Retrofitting strategies have to be applied on a case-by-case basis given all the enhancements available in the last 10 years i.e. internal arc protection, remote switching and pressure venting technology.

In the end, all power plant and control plant have an expected life span.

Selection Criteria for Equipment Forming Part of the Substation PHI

A substation contains a number of installed equipment. The following criteria was used to determine which equipment would be used in the PHI model i.e. capital expenditure (capex) during the...
investment planning stage, equipment repair times and equipment failure rates.

**Capex costs for equipment**

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Number of installations</th>
<th>Approximate Cost</th>
<th>% of overall Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP Transformer</td>
<td>1</td>
<td>R4m</td>
<td>57%</td>
</tr>
<tr>
<td>Circuit Breakers</td>
<td>5</td>
<td>R1.25m</td>
<td>18%</td>
</tr>
<tr>
<td>Current Transformer</td>
<td>15</td>
<td>R0.27m</td>
<td>3.8%</td>
</tr>
<tr>
<td>Voltage Transformer</td>
<td>2</td>
<td>R0.18m</td>
<td>2.6%</td>
</tr>
<tr>
<td>Isolators</td>
<td>1</td>
<td>R0.05m</td>
<td>.7%</td>
</tr>
<tr>
<td>Busbar</td>
<td>1</td>
<td>R1m</td>
<td>14.3%</td>
</tr>
<tr>
<td>Surge arrestors</td>
<td>18</td>
<td>R0.24m</td>
<td>3.4%</td>
</tr>
<tr>
<td>Substation facilities</td>
<td>1</td>
<td>R2m</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>R8.99m</strong></td>
<td></td>
</tr>
</tbody>
</table>

*Table 1: The percentage Capex required per equipment for a new HV substation.*

A study of the capital expenditure over the last 5 years was undertaken for the figures represented in Table 1. It illustrates 75% of the cost is represented by equipment with moving parts i.e. the transformer tap changer and circuit breakers.

**Repair times per equipment**

Repair times for transformers vary from a few hours to a few months depending on the fault, and similarly for circuit breakers, the duration of repair are in the region of a few minutes to a few weeks.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Ratio</th>
<th>Transformer</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed Base</td>
<td></td>
<td>1741</td>
<td></td>
</tr>
<tr>
<td>CAPEX</td>
<td></td>
<td>R300k</td>
<td>1</td>
</tr>
<tr>
<td>Restoration Min</td>
<td>Hours</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Restoration Max</td>
<td>weeks</td>
<td>1</td>
<td>96 weeks</td>
</tr>
</tbody>
</table>

*Table 2: The repair times for circuit breakers and transformers.*

In the case of circuit breakers, a workshop repair may entail retrofitting, especially where spares availability for older technology is scarce. In the case of transformer, it may take 18-24 months to manufacture a new transformer, where it is no longer feasible to repair the failed transformer.

**Equipment failure rates**

The equipment failure rate indicates how many instances of equipment are failing. An annual rate is usually adopted, as can be seen in the literature review [2]. The network performance indices have been the major source of reliability measurement for Eskom Distribution and its main focus is managing the impact of supply interruption, planned or unplanned, to the customer. Utilities, world-wide, also make use of this measure as an indication of reliability [3].

By managing the equipment failure rate one has the opportunity to influence future designs, improve maintenance practices and cater for environmental influences.

- **Transformers**

Fig. 2 illustrates that the smaller MVA rated transformers contribute to the larger number of failures. This is expected, as this group represents the majority of the installed base. An average failure rate of 0.55% is calculated based on the assumption of 1% growth per annum for transformers [4]. Conducting a sensitivity analysis for this figure, and assuming a 2% growth per annum, raises the average failure rate to 0.56%.

Therefore, the transformer reliability for Eskom Distribution compares favourably with the figures...
produced in the EPRI report 1001707 [2]. Here, 2% was determined as a low failure rate with 7% being a high failure rate.

- **Circuit Breakers**

  Failure Rate:
  
  Number of failures/Installed Base/Period
  
  \[
  57/1048/14 = 0.00388 \text{ or } 0.388\% \] [5]

  Observations:
  During an investigation of the MV voltage circuit breaker performance, it was found that the circuit breakers are not suited for the intended application i.e. auto-reclose. The mechanism was originally suited for a cable-fed network as opposed to conductor-fed overhead line networks. This investigation provides valuable information toward scoping a future asset replacement strategy for these circuit breakers.

  This failure rate for circuit breakers is slightly higher than the low failure rate figures published by EPRI report 1001707 [2]. A low failure rate is 0.3% and high failure rate being 2%.

  Benchmarking of failure rates for the Eskom Distribution networks are currently being modeled.

**Development of the Substation Plant Health Index Model**

Based on the information analysed, the transformers, tap changers and circuit breakers will be selected as part of the Substation Plant Health Index. See Fig. 3. For Eskom distribution networks, figures available in 2007, show that we there are 4514 Transformers and 18421 circuit breakers.

- Movable parts are prone to wear, and circuit breaker duty will vary from the network supplied, as well as network fault current levels.
- Restoration times for the two pieces of equipment are lengthy if no other planned or network contingency has been established.
- The tap changer has movable parts by definition, and thus also requires periodic maintenance. Furthermore, as the tap changer has been sited as the second highest component failure next to windings in a report of 2007 [6]. Jagers [5] finds that tap changer failures represent 22% of the failed components.
- It enhances the Transformer model proposed by Geldenhuis [1] by including the tap changer.

Failure in oil-filled circuit breakers has often been found to be catastrophic. The insulating oil properties deteriorate and become flammable during arcing or thermal runaway. Reports indicate that damage to neighbouring equipment occurs and even 3rd party damage.

This plant health indicator will suffice as a short term measure.

**Equipment maintenance strategies**

Asset management principles have developed over years with many studies focused on the different maintenance strategies:

- Replace it when it fails
- Time based maintenance
- Condition-based maintenance
- Reliability Centred maintenance

For these strategies, a study of the equipment is conducted upfront. This study is known as Failure Modes and Effects Analysis (FMEA). Such an initiative entails identifying each component in the equipment and describing the function, as well as understanding the impact of its failure with respect to the overall equipment function. Typical maintenance tasks include routine inspections or visual inspections; minor services, routine testing of major servicing or a combination of them. This process involves a coordinated approach between:

- Equipment Designers
- Manufacturers
- Subject-matter experts
- Maintenance crews

![Circuit Breaker PHI Transformer PHI + Tap Changer PHI + Substation PHI = PHI](image)

*Fig. 3: Plant Health Index Model for Distribution Substations.*

The following are reasons:

- CAPEX is most significant for these equipment

<table>
<thead>
<tr>
<th>Large Transformers</th>
<th>Power Transformers</th>
<th>Circuit Breakers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Inspection, each month.</td>
<td>Inspection, each month.</td>
<td>Meter readings: cyclo</td>
</tr>
<tr>
<td>Meter readings: cyclo</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3: The maintenance strategies for the equipment.

Table 3 lists the maintenance strategies, courtesy of Eskom Distribution [8]. The results of these routine tests during commercial operation will be the measures for the for the development of the PHI.

During the wear-out stage of the equipment life cycle, a point will be reached where the equipment can no longer be maintained cost-effectively, and thus a decision for replacement is undertaken. This is depicted by the saw-tooth behaviour (hazard function) illustrated in Fig. 5[3].

Fig. 5: Hazard function describes the probability of failure in time (sawtooth behaviour).

A plant health index will be reviewed each time, a failure or intrusive maintenance occurs. This is because periodic or planned maintenance restores/preserves the intended function of the equipment.

It is believed that the next step for this model will be the failure prediction stage. Prediction is influenced by design integrity, network operating conditions, climatic conditions and quality of maintenance.

**Proposed Solutions (Models)**

Three alternatives were considered during the development of the substation plant health index.

**Model A (Summated PHI)**

In Model A, a simple approach was taken by summing the different values of the equipment routine test results. However, where multiples of equipment exist i.e. >1 transformer or multiple feeder circuit breakers, the substation PHI just runs away. This provides difficulty in having a credible range per in-specification (good), alarm and unacceptable (urgent) rating.

**Advantages:**
- Simple mathematical approach where tests results values are easily summated.

**Disadvantages:**
- A good rating for TDCG PHI Score tends to 0. Thus it counters the summation of the other tests. The substation PHI is not reflective of the “bad” TDCG score.
- There is no representation of individual equipment PHI.
- The end score is a challenging number to manage.
Thus the equipment PHI score is an average of the number of installed units.

**MODEL B (9-point PHI)**

In order to overcome the challenge working with a summated score system, a converted score model was developed.

The routine test results are converted to a score between 1 and 3 where 1 = a good score, 2 = an alarm score and 3 = an urgent score. The blue phase of the F1 circuit breaker has a contact resistance value of 842. Table 7 lists the contact resistance test limits for the particular MV circuit breaker [9]:

<table>
<thead>
<tr>
<th>Range</th>
<th>Score</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;100</td>
<td>1</td>
<td>Good</td>
</tr>
<tr>
<td>Between 101 and 280u-ohm</td>
<td>2</td>
<td>Alarm</td>
</tr>
<tr>
<td>&gt;281</td>
<td>3</td>
<td>Urgent</td>
</tr>
</tbody>
</table>

*Table 7: The health measures for contact resistance of MV circuit breakers.*

Therefore, a rating out of 3 for each of the 9 tests is developed. In this model, an average score is used for the instances where multiples of equipment exists. In the model itself, each individual piece of equipment is managed.

Advantages:
- Each piece of equipment will have an individual PHI rating.
- Simple scoring model to manage.

Disadvantages:
- None.

- **Health Measures for the 9-point Substation PHI Model:**

A Sub Score of 0-2 points mean that there are a maximum of 2 test results that are of concern. We will call this score a Good Rating. This is because we can always expect WC and kV for an OLTC to deteriorate with time. We have at least 2 routine tests defined per Equipment.

**Action would be:** Investigate equipment performance record and the work order feedback reported, and action accordingly. Continue monitoring all other Equipment, as per normal.

A Sub Score of 3-5 points mean that there are 5 test results that are Problematic. We will call this an Alarm Rating. This is because we can always expect WC and kV for an OLTC to deteriorate with time, as in 1.1 above. The Sub PHI Score of 5, indicates problems with at least 2 pieces of equipment out of the 3.

**Action would be:** Immediately action the abnormalities, conduct probability of failure analysis and evaluate the contingency plan.

A Sub Score of >6 points mean that there are abnormalities encountered with all 3 pieces of equipment in the Substation. Probability of failure is raised.

This score would be an Urgent Rating.

**Action would be:** Action maintenance issues and consider revised maintenance strategy to maintain current service levels. Unforeseen opex expenditure is encountered here. Re-prioritise the completion date of refurbishment project. A comprehensive Risk Model is to be conducted. Contingency plan should be ready to be activated.

**Model C (17-point PHI)**

We now have a total of 17 individual tests that are being monitored. Based on the same principles as in Model B however each phase of the circuit breaker is represented in the final substation PHI score.

Advantages:
- Simple scoring model to manage.

Disadvantages:
- The circuit breaker is overrepresented in the substation PHI rating. It counts 40% to the substation PHI, but consists of 12 tests.

**Equipment Health Measures**

The substation plant health index will be represented by a series of 9 tests (Model B) as shown in Table 4.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Plant Health Measure</th>
<th>Test</th>
<th>Weighting per Equipment</th>
<th>Sub PHI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circuit Breaker (High voltage and medium voltage)</td>
<td>Contact Resistance Test per phase</td>
<td>30%</td>
<td>40%</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Penetration test per phase</td>
<td>30%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Closing time per phase</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tripping</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4: The weighted plant health measures per equipment.

Each test has been weighted based on interviews held with the various subject matter experts including field staff and technology specialists. A flow diagram for the proposed substation plant health index is shown below in Fig. 4.

![Flow diagram for the substation plant health index.](image)

**Fig. 4: Flow diagram for the substation plant health index.**

The work instruction is a detailed step-by-step specification for intrusive maintenance, containing the threshold limits required for each routine test during in-service conditions.

Where tests are within specification, no further action is required. However, where routine results are out of spec, an investigation is necessary. This investigation may be simple, where the field operator has noted that re-building of the mechanism is required, or moving contacts may need to be replaced at the next intervention. A corrective action is required.

There are rare cases where equipment can be energised if one of the routine tests has exceeded the limits. This decision requires careful consideration and is often the decision taken by the specialist in consultation with relevant staff. The customer supply is restored but, a follow-up action is planned immediately. Often, abnormal spare or replacement parts may be needed, and the repair time for the defect, may be longer.

**Reporting Requirements**

The substation model is easily implemented using Microsoft Excel. The conditional formatting function allows you to program visual indications of the severity of the equipment routine test result. In this instance, the following applies for the model:
- RED = 3
- YELLOW = 2
- GREEN = 1

Furthermore, Fig. 9 below illustrates the substation PHI scores for a number of substations. Here, the substation PHI is scored as follows:
- RED = >5
- YELLOW 3-5
- GREEN <=2

<table>
<thead>
<tr>
<th>Substation</th>
<th>PHI Score (Current Year)</th>
<th>PHI Score (Following Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>6</td>
<td>4.5</td>
</tr>
<tr>
<td>B</td>
<td>6</td>
<td>4.5</td>
</tr>
<tr>
<td>C</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

**Scenario**

In the following year, the rating of 6 comes down to 4.5. This indicates that an intervention improved reliability levels.

I believe that having status such as:
- Investigation completed Yes or No
- Maintained Yes or No
- Replacement required

for all RED zone scores will improve the monitoring of the equipment or substation PHI.

**Fig. 10: Dashboard management principles used for Substation PHI model.**

The above scenario confirms the sawtooth behaviour of equipment with moving parts (circuit breakers and tap changers) that was described earlier.
Results using Model B

The routine test results of four distribution substation were sourced, and used for the simulation. In the same used, transformer sizes varied between 5 and 20MVA and the MV circuit breakers were of oil and SF6 insulating technology. The substation PHI results are shown in Table 10.

<table>
<thead>
<tr>
<th>Substation</th>
<th>CB PHI</th>
<th>Trfr PHI</th>
<th>OLTC PHI</th>
<th>Sub PHI</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5.313</td>
<td>1.6</td>
<td>1.8</td>
<td>3.1052</td>
</tr>
<tr>
<td>B</td>
<td>4.725</td>
<td>1.6</td>
<td>1.8</td>
<td>2.87</td>
</tr>
<tr>
<td>C</td>
<td>4.000</td>
<td>2.0</td>
<td>1.8</td>
<td>2.78</td>
</tr>
<tr>
<td>D</td>
<td>3.857</td>
<td>2.0</td>
<td>1.8</td>
<td>2.72</td>
</tr>
</tbody>
</table>

Table 10: Simulated results for the information of 4 substations, using the alternative B model.

Transformer reliability ranges between fair and good for the substations evaluated. In all 4 cases, we find circuit breaker health to be of concern. A detailed investigation is required as the next step in order to determine normal ageing, or areas of risk for the circuit breakers.

In sample B, one of the CB routine test results was not available. If one assumed the same performance for this breaker as the others, the substation PHI score increases by 30%, but the substation PHI still remains in the Alarm zone.

For sample C, the Transformer PHI is skewed. The water content value must be evaluated in conjunction with the temperature at the time of sampling i.e. we expect the water content to be “higher” for lower operating temperatures, typically observed with the lighter loaded transformers. For sample C, a capex project has already been approved for replacement of the circuit breaker. The target completion date can now be influenced based on the PHI evaluation.

In the last sample, D, the same findings were made for the WC as in the previous case for the transformers. One of the installed seven circuit breakers, needs attention however, whilst the rest are in the alarm stage, indicating on-set of the wear-out stage. The circuit breakers are 25 years old.

Evaluation of Model A

Till now, the substation health was largely represented by the condition of the transformer condition. The model shows:

Transformer PHI Results:
Substation A: Good, 28 years old
Substation B: Good, 18 years old
Substation C: Good, 30 years old
Substation D: Good, 23 years old

The average age of the Transformers analysed was 24.75 years old.

Circuit Breaker PHI Results:

Substation A:
The medium voltage (MV) circuit breakers are showing early signs of wear. The closing and tripping times of all the MV circuit breakers were out of specification.

Substation B:
The MV circuit breakers are of a concern. Similarly, closing and tripping times were out of specification. Furthermore, the contact resistances of 75% of the installed base were out of specification.

Substation C:
Feeder 1&2 of the MV circuit breakers are showing early signs of normal wear and tear. Investigate the abnormal contact resistance values. Feeder 2 and 3 have unacceptable readings for tripping times and needs to be investigated.

Substation D:
Circuit breakers are showing early signs of wear. Again, closing and tripping times are of particular concern.

The oil sampling of transformers and tap changers has been outsourced for approximately 7 years and provides the required asset management advantage [1]. However, switchgear is 5-6 times larger in numbers and is challenging to manage with an already declining skills base. In rare cases, maintenance spares for aged switchgear may no longer be readily available.

The substation PHI model at this early stage provides valuable information about MV circuit breaker condition to the organisation. Once the model is fully implemented, much more may be revealed about tap changer condition.

Conclusion

The following conclusions are made:

a. Eskom Distribution now has a dashboard indication of the plant health for its circuit breakers and tap changers installed at its Dx substations.

b. A policy to replace transformers at 30 years is not justified. However, circuit breakers are failing just at the 25 year investment period.

c. Reliability trending is limited, with only 1 set of test results available.

d. The substation PHI requires review, as equipment condition will be affected by failures or operating conditions.

e. The model provides an opportunity to influence network contingencies and strategic spares stock holding.
f. Provides input into forecasting of OPEX and CAPEX budgets.

Acknowledgements

The author would like to acknowledge the contributions from Ulrich Minnaar, Lester Geldenhuis and Siraj Williams.

References


Authors Address

E. Brand
Eskom
P.O. Box 222
Brackenfell 7561

W. Fritz
School of Electrical Engineering
Cape Peninsula University of Technology
P.O. Box 1906

U. Minnaar
Eskom
P.O. Box 222
Brackenfell 7561