Reliability assessment for medium voltage electrical network: A case study within Eskom distribution

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Abstract: The main purpose of the Electrical Power System is to provide a safe and acceptable electricity supply to the customers, with a reasonable level of reliability. Within Eskom, the serious effect of the unreliable power supply is a perpetual concern. Distribution network system is still liable for more than 80% of the customer reliability issues with the majority of faults (70%) occurring on the Medium Voltage (MV) networks. This paper is aimed at identifying the issues that contribute to poor reliability within the MV network and mitigation factors. This is intended to assist electrical utilities effectively to investigate the affected network, and to be able to apply strategic reliability improvement plans to achieve optimal performance. A case study was used to conduct the research, and the study area focus was Taunus electrical supply area within Eskom's Distribution.

Keywords: SAIDI, SAIFI, Reliability, Distribution Network, Medium Voltage

1 INTRODUCTION AND PROBLEM

In recent years, electricity supply plays a very crucial part in people's lives, but just having access to electricity is not sufficient; the reliability of electricity supply is also important [1]-[2]. "*Reliability of service must be outstanding; usually less than two hours without power per year, (99.98% availability) is considered a reasonable level of power availability, and a lot of power supply utilities are striving to limit the time that an average customer is without power to less than one hour per year*" [3].

Reliability refers to the frequency of equipment failures per equipment type, the exposure of the equipment to external causes, the number of customers exposed to supply interruption when faults occur and the duration of supply interruptions when faults occur [4]. The basic used reliability measures by most electrical utility are the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) [5]. The measurements are illustrated in the Table 1.

Table 1: Table 1: Key performance Index [6]-[11]

Key performance Index within Eskom	Formulas
System Average Interruption Duration Index (SAIDI)	SAIDI = $\frac{\Sigma \text{ Customer Interruption Durations}}{\text{Total Number of Customers Served}}$ = $\frac{\Sigma \text{ ri Ni}}{\text{NT}}$ Where ri is the restoration time for event i, Ni is the number of interrupted customers for sustained interruption event i during the reporting period and NT is the total (average) number of customers served for the reporting period.
SAIDI gives an indication of the average duration of customer interruptions within reporting area per reporting period (usually per annum).	
System Average Interruption Frequency Index (SAIFI)	SAIFI = $\frac{\Sigma \text{ Number of Customer Interruptions}}{\text{Total Number of Customers Served}}$ = $\frac{\Sigma\text{Ni}}{\text{Ti}}$ Where Ni = Number of interrupted customers for sustained interruption event i during the reporting period, NT = Total (average) number of customers served for the reporting period.
SAIFI provide the average number of customer interruptions within a reporting area over a reporting period (usually per annum)	

It has been reported that outages in the distribution network system are still liable for more than 80% of the customer reliability issues [5] with the majority of faults (70%) occurring on the Medium Voltage (MV) networks, and 20 % of faults are related to events on the distribution Sub-Transmission [6]. This is because, previously, the distribution system was given less priority regarding reliability planning compared with the transmission and generation systems [5]. This is due to the fact that the distribution system is considered to be cheap compared with the generation and transmission system, and its effect is limited to a small area. This results in less effort being devoted to improving reliability within the distribution network [7].

Previously, the criteria used by the network planning and design Department was to increase the number of customers who could be connected, based on the funding available. The old network planning and design criteria was concentrated on the voltage regulation limits, and making sure that the thermal and fault levels were not surpassed [8]. As a result, a number of long radial feeders were created on the Eskom distribution and transmission network, without considering an option for alternative supply in the event of faults in the network. Then, Eskom distribution started to experience major outages on the network [8].

Today, "outages in the Eskom Distribution network accounted for a significant majority of the total outage durations experienced by Eskom Distribution customers" [8]. In 2010, the level of network performance within Eskom distribution was poor compared with international benchmarks. As a result, Eskom distribution is continuously under considerable pressure to improve its network performance and to ensure improved future first quartile performance in international benchmarking analyses [9].

One of Eskom's targets is to become one of the top five well-performing utilities in the world. It is therefore important that Eskom improves the reliability of its distribution network to acceptable targets, as this will assist Eskom in meeting this target.

As a business, Eskom will then be required to make a huge investment in improving reliability of the network, but before money can be spent, it is important to investigate the causes and define the problems that lead to the poor performance of MV distribution networks, resulting to unreliable networks.

This can be done firstly by understanding the underlying problems that exist within Eskom's distribution network, which lead to unavailability of network when a fault has occurred, and also by defining the causes of these problems, and by quantifying them per electrical feeder.

Since the MV distribution system is the largest contributor to poor reliability, the research study was limited to the Medium Voltage network. A case study and comprehensive literature review will be used in order to complete the research study. Due to the complexity of the overall distribution network and limitation to data access in other utilities or distribution networks, the study area focus will be on the Taunus Distribution Supply area within Eskom's Distribution Network, to allow access to data.

2 RESEARCH OBJECTIVES

The objective of the research is to identify, define, and quantify factors that lead to poor reliability of distribution networks. From the findings, alternative solutions will be proposed and discussed based on the findings of the study. This is intended to assist electrical utilities to investigate the affected network effectively, and to be able to apply strategic reliability improvement plans to achieve an optimal performance.

3 RESEARCH METHODOLOGY

Reliability is defined as a measure of performance - dependability and system reliability as the probability that the system will perform its intended function for a specific interval of time under stated conditions [10]. The basic reliability measures used by most electrical utilities, within the load point, are: the average failure rate (SAIFI), and the outage duration (SAIDI) [5]. Eskom distribution secondary data was collected to produce the results. Figure 1 presents the research methodology followed and each building block is further discussed in detail in the subsections.

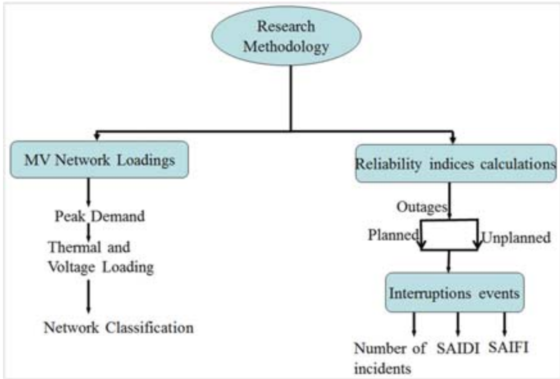


Fig. 1: Research methodology [4]-[9]-[11]-[22]-[23]

3.1. MV network loadings

This section illustrates high level step by step process to be followed when conducting constrain MV feeder assessment. SmallWorld software was used to import feeder to the recommended assessment system i.e. ReticMaster software. To conduct the simulation, maximum demand values were required. The maximum peak demand values for each feeder were obtained from the metering statistic system within Eskom.

The data was obtained in the form of active and reactive power, so to calculate the apparent power the formula below was used [22]:

$$S = \sqrt{P^2 + Q^2} \quad (1)$$

Where S (kVA) is apparent power at the source, P (kW) is Active power at the source and Q (kVar) is Reactive power at the source.

After calculating the maximum apparent power, the value was calculated on the source of the feeder in Reticmaster to obtain the maximum thermal loading and minimum voltage loading.

Maximum thermal loading was calculated from the peak demand value using [23]:

$$\textit{Thermal Loading}\,(\%) = \frac{S_{loading\,(kVA)}}{S_{Conductor\ rating\ (kVA)}} = \frac{I_{normal}}{I_{base}} \quad (2)$$

Minimum voltage loading was calculated from the minimum demand value using [24]:

$$V_{End} = V_{Supply} - (I_{Supply} \times Z_{End}) \quad (3)$$

Where:
V_{end} is the minimum voltage at the end of the feeder,
V_{Supply} is the source voltage,
I_{Supply} is the current of the line, and
Z_{End} is the impedance of the line.

3.2. Reliability assessment

The sub-sections below explain the calculation of planned and unplanned interruptions, including the formulas used to obtain SAIDI and SAIFI results.

3.2.1. Unplanned outage duration

The SAIDI and SAIFI values within Eskom do not necessarily include the actual occurrence time of the fault, but the time when the fault was reported. The total outage duration of an interruption was obtained by adding the times below [9].

- Dispatch time - starts when the fault is recorded in the system and ends when the driver travels to site to locate the fault.
- Travel time – starts when the operator travels to the site and ends when the operator starts to isolate the faulty part of the network.
- Sectionalising time – starts when the operator performs the switching in the network with an aim to isolate the faulty part of the network.
- Fault finding time – at this stage the faulty section on the network will be isolated and the operator will be conducting visual inspection to identify the fault equipment.
- Repair time – at this stage the faulty equipment is repaired and only the customers within the faulty network are affected or without power supply.
- Switching restoration time – at this stage the faulty equipment is returned to its original state.

3.2.2. Planned outage duration

Planned outage durations involves all planned maintenance conducted on the network. The frequency of maintenance events differs for each component on the network and is subjected to supplier specifications. The duration of the maintenance events specify the time when the customer was not supplied as a result of maintenance being performed on the network. During maintenance, several customers may be without power supply. So, for each component type, a certain percentage of customers affected are set [9].

3.3. Interruption data per root cause

The interruption information per root cause was arranged to show the total number of incidents, the total customer hours and total customer interruptions.

4 TAUNUS MV FEEDER NETWORK

The Taunus CNC 11kV MV distribution network is illustrated in Figure 2. The green lines show a total of 21 MV feeders, which are currently taking load, and their respective substations' location. The dotted lines indicate that the feeder is a cable while the solid lines indicate an overhead line.

Fig. 2: MV feeder network for Taunus substation [25]

5 RESULTS

5.1. MV network loading statistics

Figure 3 below illustrates the loading statistics of the 11kV MV feeder in percentage, where the red colour illustrates the percentage of the overloading feeders, orange colour indicates the percentage of feeders which are about to reach the overloading level and the green colour illustrates the percentage of feeders that are not overloading.

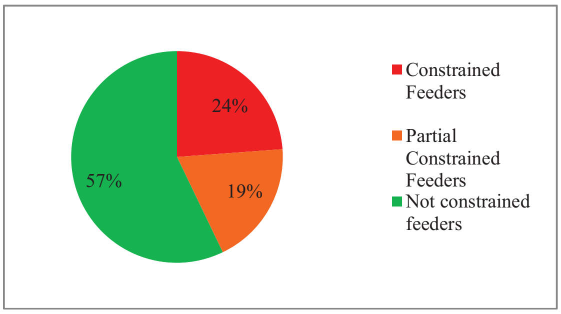


Fig. 3: 11 kV feeder loading statistic [26]

5.2. Taunus CNC reliability performance: SAIDI and SAIFI

The overall Taunus CNC network reliability performance (SAIDI and SAIFI) for the past three years is shown in Figure 4 below.

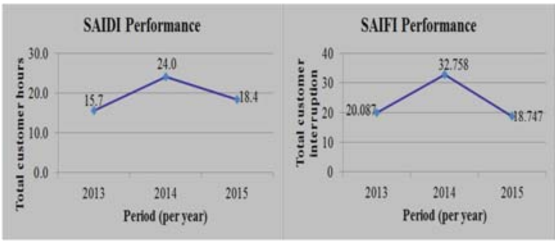
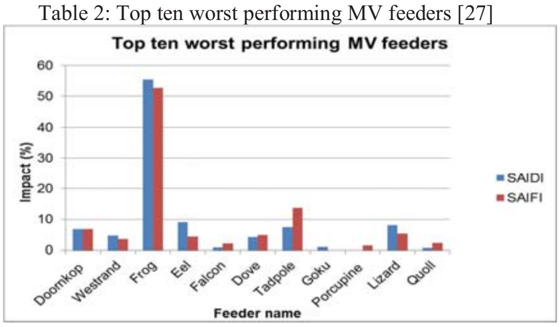


Fig. 4: SAIDI and SAIFI for Taunus MV network [27]

5.3. Worst performing feeders

The top ten worst performing feeders, which contribute to the SAIDI and SAIFI performances within the Taunus area of supply, are presented in Table 2.

Table 2: Top ten worst performing MV feeders [27]



5.4. Network failure root courses

Figure 5; indicates the total number of incidents within the Taunus CNC. Defective equipment resulted in 124 faults, 45 from overhead power line problems, 44 from maintenance related faults, 23 from weather, 21 from fuse failures, 15 from unit equipment problems, 8 from foreign objects, 5 failures related to vandalism and 8 faults related to fire.

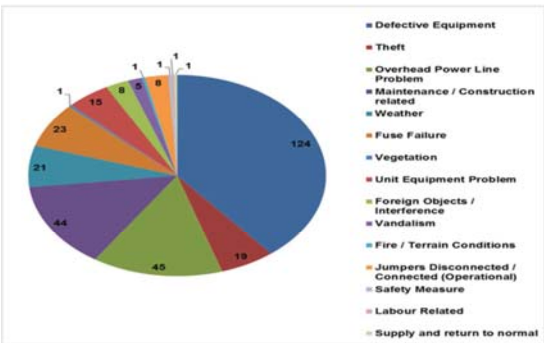


Fig. 5: Total number of incidents [27]

The detailed breakdown of the total number of incidents is illustrated in Figure 6. The breakdown failures indicate that 26 of the faults were related to LV network failure, due to overloading in the transformers, 38 from jumper failure, 33 from power transformer related failure, 23 from fuse failure, 12 related from cable failures, 10 faults related from drop out expulsion fuse, 15 faults from equipment related, etc. This is shown in Figure 6.

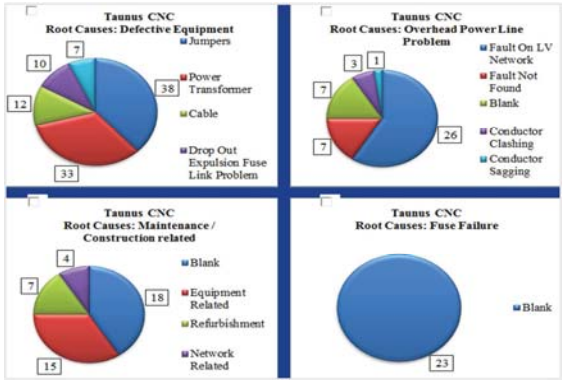


Fig. 6: Failure root causes breakdown [27]

Figure 7 indicates the total customer interruptions due to network failures within the Taunus CNC, whereby defective equipment failure resulted in 149 492 customer interruptions, 40 244 due to theft, 27 150 due to maintenance, 15 072 due to overhead power line problems, 14 664 due to fire/terrain conditions, and only 28 626 customers were interrupted due to other faults in the network.

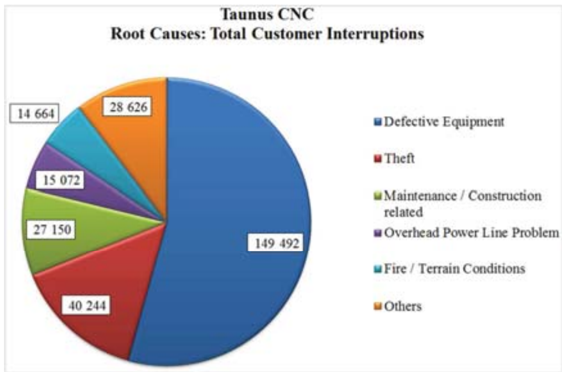


Fig. 7: Total customer interruptions [27]

The breakdown of the total customer interruptions in Figure 8 indicates that cable faults resulted in the highest number of customer interruptions of about 46 980, followed by cable theft interrupting almost 32 157 customers.

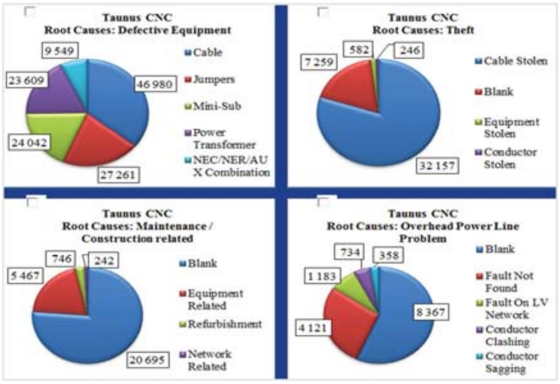


Fig. 8: Total customer interruptions breakdown [27]

Figure 9 indicates the total customer hours lost due to network failures within the Taunus CNC, whereby defective equipment failure resulted in 183 741 customer hours lost, 17 481 hours lost due to maintenance, 17 145 hours lost due to overhead power line problems, and 14 213 due to unit equipment problem.

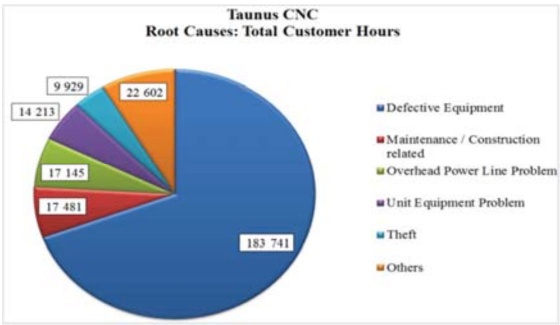


Fig. 9: Total customer hours lost [27]

The breakdown of failures in Figure 10 indicates the customer hours lost, whereby, cable faults resulted in 85 381 hours, 14 213 hours lost due to overloading, 27 683 hours lost due to power transformer faults, 26 645 due to jumper faults, 20 059 hours lost due to mini-sub failures, etc.

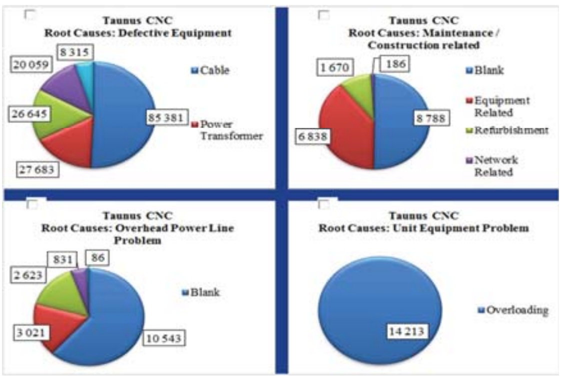


Fig. 10: Total customer hours lost breakdown [27]

5.5. *Factors contributing to poor reliability*

Figure 11 illustrates factors contributing to poor performance as a percentage.

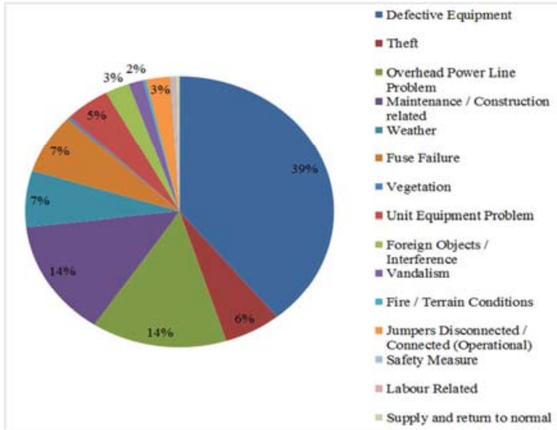


Fig. 11: Factors contributing to poor reliability [27]

6 FINDINGS

The case study results in Figure 3 indicate that the reliability performance within the Eskom-Taunus supply area was poor, since the number of hours was greater than two hours without power per year. Eskom - Taunus network reliability performance results in Figure 3 indicated a SAIDI of 15.7 hours in 2013 and this figure increased dramatically to 18.4 hours in 2015. The SAIFI average was 20.087 in 2013 and it dropped by 6.67% to a figure of 18.747 in 2015. During 2014, both the SAIDI and SAIFI averages were very high compared with the other years.

About 24% of the feeders within the Eskom -Taunus distribution network were overloaded. This is indicated by a red colour in Figure 2, while 19% of the feeders were about to reach the overloading level. The overloading was caused by illegal connections.

The result indicates that the problematic network type was cable network, particularly the double end fed design with a normal open point having a remote terminal unit connected to it. In Table 2 the frog feeder is a cable network consisting of remote terminal units. Frog 11kV feeder was the worst performing feeder, causing a huge impact on both SAIDI (55.4%) and SAIFI (52.62%).

The cause of interruptions were defective equipment, overhead power line problems, maintenance or construction related; fuse failure, unit equipment problems, vegetation, theft, weather, foreign objects, jumper disconnected and vandalism, as illustrated in Figure 4.

The results in Figure 10 indicated that defective equipment contributed the most to poor reliability. About 39% of the total lack of reliability is due to defective equipment: failures on the jumpers, power transformers, cable, breaker/switchgears, circuit problems, and drop out expulsion fuse link problem. We also have the following defective equipment: insulators, isolators, line conductors (infrastructure), mini-subs, neutral earthing resistors or compensators and auxiliary transformer combinations, and towers/structures/ poles.

Referring to Figures 4, 6 and 8, defective equipment gives the highest total number of incidents amounting to 124, which, resulted in the highest total customer hours lost and interruptions of 183 741 and 149 492 respectively. The main contributor was cable faults, amounting to 33 (Figure 5), which resulted in the highest total customer hours lost and interruptions of 46 980 (Figure 7) and 85 381 (Figure 9) respectively; of which 35 157 out of 85 381 total customer interruptions were due to copper cable stolen.

7 RELIABILITY IMPROVEMENT STRATEGIES

According to [20] historical assessment approach is the only practical way of improving reliability of the power supply. Gathering information on what triggered interruptions to one or more customers is the key fundamental of a good reliability programme [21]. It is therefore possible for Eskom to improve reliability within MV distribution, since historical network data illustrating the factors affecting the reliability is available. This can be done by utilising Figure 12 below, which illustrates the components which contribute to a reported SAIDI and SAIFI, within the MV feeder distribution network [9]. Figure 12 illustrates the overall factors that affect the MV distribution network.

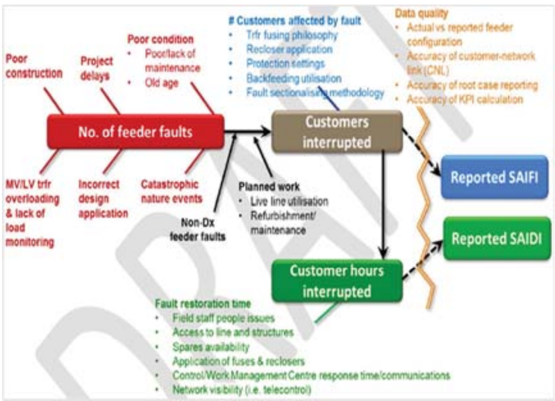


Fig. 12: SAIDI and SAIFI cause and effect diagram [9]

This can be applied by electrical utilities to explain the various opportunities regarding network performance improvement. Although addressing these issues will come at a cost, it is still possible to maintain a stable power supply, even with low tariffs [1].

The real issues Eskom needs to address are to reduce the number of faults, limit the impact of outages and the duration of outages, by applying capital, operational and maintenance interventions. The proposed or existing network can be designed to minimise all the above at optimal cost [4]. Table 3 below illustrates the capital, as well as the operational and maintenance interventions that can be applied to improve reliability.

Table 3: Network reliability improvement strategies and interventions[4].

Network reliability improvement strategy	Capital interventions	Operational and maintenance interventions
Reduce the number of faults	Address constrained networks	Increase the frequency of lines and substations inspections to identify early signs of equipment failure
	Apply more robust substation or line designs	
	Refurbish substations/lines that are in poor condition	More proactively planned maintenance
Limit the impact of outages	Reduce the number of customers per feeder by adding more feeders or splitting existing feeders	Optimal sectionalising of the network to temporarily restore supply to as many customer as possible
	Add additional lines and substations for redundancy	
	Implement fuses at transformers	
	Add reclosers to isolate upstream network from faults	
	Use back feeding capability where it exist	
Limit the duration of outages	Install substation remote terminal units and faults path indicators	Reduce dispatch time
		Reduce travelling time
	Implement distribution automation	Reduce time to sectionalise the network and locate the faults
		Improve repair time through better access availability of the correct spares and tools, etc.

Firstly, the case study results indicate that defective equipment contributes 39% to poor reliability, and is the highest contributor. The main cause of defective equipment problems results from the lack of maintenance. It has been stated that when the equipment is available for maintenance there is no funding to perform the maintenance. Similarly, when the funding is available, the equipment is not accessible to perform the required maintenance. As a result, defective equipment could be minimised by improving the traditional outage based maintenance options for the future continuous monitoring and trending maintenance options [28]. The upgraded maintenance plan contains continuous monitoring and trending maintenance options per equipment type, and this is indicated in Table 4.

Table 4: Continuous monitoring and trending options.

Equipment	Continuous Monitoring and Trending Maintenance Options
Switchgear bus—bare	Partial discharge, temperature, humidity, floor water
Electric utility	—
Switchgear bus—insulated	Partial discharge, temperature, humidity, floor water
Cable terminations	Temperatures, humidity, water
Bus duct	Bus duct temperatures, humidity, water
Transformers	Tx temperature, moisture, dust (air Tx)
Generators	Partial discharge, vibration, temperature
Open wire	Periodic thermography
Cable	Temperatures, humidity, water
Cable joints	Temperatures, humidity, water
Circuit breakers	Temperatures, humidity, floor water, dust
Motors	Temperatures, vibration
Motor starters	Temperatures, humidity, floor water, dust

Continuous monitoring and trending maintenance options can be achieved by using new technology such as point-connection temperature and partial discharge detection. The combination of new technology and the failure mode predictor parameters is able to tell when the equipment needs maintenance, what maintenance needs to be performed, if the equipment has a problem now, and give the action plan regarding that specific problem [28]. Again, one of the focuses of smart-grid is uptime and reliability, aiming to predict pending failure modes on electrical equipment. The smart grid system is able to give notification related to pending failure before it occurs, and to recommend an ongoing maintenance plan [28]. It is important for maintenance managers "to understand that the maintenance functions cannot operate on their own" [18]. To achieve positive results, maintenance personnel need to partake in the overall business production strategy [18]-[19]. Large companies could utilise almost 70% of the overall workforce [18].

Secondly, the reliability of the overhead MV distribution feeders can be improved and enhanced through the use of protection network devices and switches, such as isolating links, automatic sectionalisers and reclosers, transformer fuses, back-feeding and network visibility [4].

Thirdly, the case study results indicated that unit equipment problems were caused by overloading largely due to illegal connections. The strategy for electricity theft detection is called the power loss analytical framework, which uses transformer metering aiming at identifying, detecting and predicting power loss, by studying each customer database for possible electricity theft [13]-[14]. The system uses extreme learning machine, support vector machines and online sequential extreme learning machines to analyse the data for electrical utilities, taking into account the connection of such data with the time of the day, possible weather condition plus calendar event factors [13]-[14]. The issue of electricity theft can be minimised by applying a technical solution like tamper proof meters [13]-[14]. Again, network inspection and monitoring and sometimes restructuring power systems ownership and regulations can also work [15]. The Operation Khanyisa programme to solve electricity theft is progressing slowly, so Eskom can learn from the Georgia Power Sector [16].

Fourthly, the solution to copper cable theft would be a recent strategy developed by [29], which is the use of copper bond composite cables which are difficult to cut and steal. Figure 13 illustrates the copper bond composite cables.

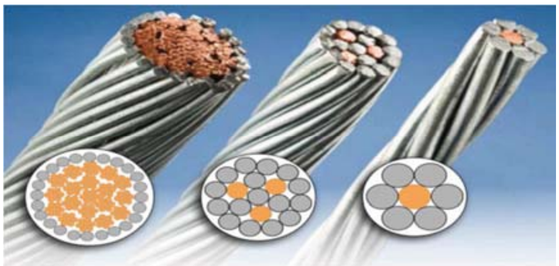


Fig. 13: Copper bond composite cables [29]

This conductor operates like a copper conductor, but its appearance is like a non-copper conductor, and it is suitable for both overhead and underground distribution networks [29]. Collaboration and leadership from all stakeholders involved is required. Monitoring the scrap metal industries for the possession of stolen cable would minimise the theft market, the trade of any second hand copper must be declared unlawful, other than centralised state owned copper recyclers. If that can be accomplished, the problem of cable theft will be resolved and, lastly, mainstreaming prevention actions throughout local safety strategies needs to be initiated, through education, youth services, community development and planning[17].

Lastly, fuse failures on an MV distribution network can be minimised by using fused servers. The device is connected in series with a fuse to protect it from transient faults. Fuse severs have the capability to clear a fault in as little as a half-cycle, before the fuse melts, and then closes after a configuration dead time. The smart fuse saver can also easily be integrated with the Remote Terminal Unit (RTU) to provide network visibility and events history of the spur line [30].

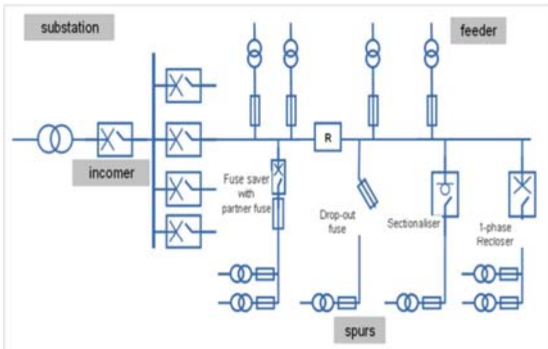


Fig. 14: The fuse server and fuse partnered on spur line [30].

However, it should be noted that the above recommendations cannot work alone. Eskom's power sector needs to invest much in information technology (Supervisory control and data acquisition) and it is interesting that Eskom is taking an initiative to partake in a smart grid technology to improve reliability [1]-

[12]. Only if these proposed solutions are implemented successfully will the reliability of power supply within Eskom improve.

8 CONCLUSION

The research objective was to identify, define, and quantify factors that lead to poor reliability of the distribution network. From the findings alternative solutions were proposed and discussed, based on the findings of the study.

The research findings within Eskom's distribution network found that the reliability performance is poor, due to defective equipment failures, overhead power line problems, maintenance or construction related failures, fuse failures, unit equipment problems and cable theft. Defective equipment posed the highest risk, since it contributes 39%, overhead power line problem contributes 14%, only 14% for maintenance faults, 6% for theft, 7% for fuse failures, and unit equipment problem contributing 5% making a total of 85%.

Several solutions were proposed to improve the reliability of Eskom's distribution, including investments information technology systems, smart grid technologies, capital, operational and maintenance strategies and reliability improvement strategies for defective equipment, overhead power lines, fuses, unit equipment and cable theft. All these items were discussed.

By applying these mitigation strategies and focusing on limiting the entire 85% impact presented by failure root causes, power cuts can be reduced from 18.747 hours to 2.75 hours. Meaning an 85% reliability improvement within Taunus' distribution supply area in Eskom's distribution.

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