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Zoning of rural medium voltage distribution networks for improving restoration time using distribution automation systems

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Abstract: Electricity distribution reliability is a measure of power availability, which is a function of the frequency of interruptions, and the duration of such interruptions. Studies have shown that Medium Voltage (MV) overhead lines are the most significant contributory factors to power outages which lead to poor performance of electrical distribution networks. The research investigated the basis for the poor performance of MV overhead lines in a 22 Kilovolt (KV) radial feeder, in order to develop the most reliable and cost effective optimization approach for switching device placement which has the potential of improving the performance of MV overhead line distribution networks. A major requirement in power distribution is to supply customers with reliable electricity without interruptions. The research explored and identified causes of electricity supply interruptions, high values of Mega Voltage Ampere (MVA) losses, and the effect of downtimes in terms of number of customers impacted by outages. The findings informed the design of a robust switching device placement algorithm, capable of optimizing the performance of a 22KV overhead line, by reducing the number of customers impacted by interruptions, and minimizing MVA losses accordingly. Optimal switching device placement strategy improved restoration time of electricity by isolating only faulty section of network, and minimizing high costs currently associated with scheduled maintenance on the MV lines. On the occurrence of momentary supply interruption, the reclosers automatically restore electric power by their auto-reclose feature. System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Customer Base Impact Index (CBII), and Mega Voltage Ampere Base Impact Index (MVABII) were used to measure the performance outcomes of the line using customer and MVA data obtained from the feeder. Secondary data comprising information on monthly SAIDI, SAIFI, customers connected per transformer, and MVA data were obtained from the engineering plant department. A switching device placement technique was developed and validated using comparative analysis of the old and new data impact obtained after a pilot implementation phase. The developed technique improved the network performance by reducing the number of customers affected, and MVA losses impacted due to electricity supply interruptions by 30.74 and 25.30 % respectively.

Keywords: Medium voltage; recloser; power distribution optimization; SAIDI; SAIFI

1. INTRODUCTION

The reliability of electricity supply to customers depends largely on the performance of power generation systems, transmission systems, and distribution system (Carter-Brown et al, 2008). In electrical power distribution systems, frequency of interruptions, outage durations and customer supply losses are the main factors often considered to judge the reliability and performance of distribution networks. According to Sohn et al (2006:941) more customers affected may cause heavy damage by increasing interest in the value-based reliability optimization. The study was carried out at a robust power distribution network herein referred to as ‘feeder A’, situated in location A of area B within province C. The study was divided into phases with the ultimate aim of developing a model for improving the reliability of the power distribution network. Key Performance Indicators (KPIs) of Medium Voltage (MV) Overhead line distribution networks were evaluated which is highly important in a bid to identify where and how to improve reliability of electric power supply to customers as required by the utility company. In the power distribution industry, the main problem associated with power systems is lack of stability due to intermittent power failures. Poor reliability is linked to incessant emergence of unforeseen defects (third party influenced, natural causes and hardware failures) which are often complex, and require extensive time to diagnose and repair. Another major challenge is linked to the landscape/geographical expanse MV overhead line distribution networks cover (Hannan, 2011:235). According to Abdi et al (2014), about 70 percent of power failures are estimated as transient faults, and about 30 percent are permanent faults on MV networks. Based on the findings of the study carried out on different feeders within the “feeder A” network, the most contributory factors to poor performance of the MV overhead lines were found to be unplanned interruptions associated with hardware failure, environmental causes, natural occurrences, and third party actions. Unplanned maintenance and major interruptions are the most contributors to the Reticulation Supply Loss Index (RSLI). As highlighted by Hashim et al., (2006: 586), transient faults are commonly caused by defects due to MV line interferences as a result of clashing power lines caused by stormy whether effects. Conversely, permanent faults were mainly associated with broken lines (hardware) and third party activities such as theft and vandalism (Thomas, 2014).

In power system design, the user end expectations need to be factored into the design and these considerations must inform the approach adopted. Customer satisfaction is largely influenced by the level of reliability which is commonly understood by end users as a state where there is continuous uninterrupted power supply round the clock. As power systems designs are becoming advance by the day, the possibility of applying technology for effective network monitoring is now a reality. In this regard, it is important to deploy solutions with some level of intelligence built into them. One of such approaches is the use of switching device placement optimization technique to improve the performance of MV overhead line distribution network in order to achieve the objective of reducing the possible number of interruptions, outage durations, number of customers affected and MVA loss.

Power systems equipment are highly capital intensive and equipment replacement requires extensive budgeting and planning. For this reason, power system designers try to achieve as much as is possible for system reliability within project budget for the envisaged lifecycle of systems. Due to the problem associated with equipment’s life span, eliminating power disruptions is a herculean task. Elimination as against minimization of failures has been a hard to reach goal. In this study, switching devices placement optimization technique was adapted as a basis for proposing the new technique developed specifically for dividing Medium Voltage (MV) distribution network in “location A” into zones. Protective devices such as fuses, reclosers and isolating switches plays important role in reducing annual failure rate and outage duration and total customer interruption cost (Sohn et al., 2006:941). A total shut down of the power system in location A was not possible during the study, because the cost associated with just a few minutes of downtime is extremely enormous. This posed some limitation to the research at the start, however; during the pilot test phase, various sections of the zones were shut down for the purpose of achieving the planned objectives.

Various methods currently exist for accomplishing performance measurement of different sections of power systems. For MV lines, System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI) by (Chatterton. 2004), Mega Voltage Amperes Base Impact index (MVABII) and Customer Base impact index (CBII) are generally considered (Eskom. 2012). The study adopted existing methods and these were applied in developing the optimal switching placement technique discussed in this paper.

2. BACKGROUND

The 22KV overhead line radial feeder in location A is one of the twenty (20) worst performing feeders in its zone within a province in South African power utility. According to Carter-Brown et al (2008), reduced performance is associated with decrease of tariff and less revenue generated. As with most electrical Infrastructure, this overhead line distribution network experiences both planned and unplanned outages (Moradi et al. 2008). Planned outages occur when the equipment is isolated for reasons such as scheduled maintenance and customer request. Unplanned outages occur when power supply from the line is interrupted due to defects, leading to an automatic power trip off by protective devices. Data on restoration and daily sequential reports, Overcurrent (O/C), Sensitive Earth Fault (SEF), and Earth Fault (E/F) protection triggers recloser within the 22KV feeder system available at location A was utilized for the developed model.

Overhead line performance evaluation is important to the utility where the study was conducted because it guides them in identifying where to make improvement on the distribution network. Improving the performance of the distribution networks is important to ensure reliable electricity supply is available to end users (Carter-Brown et al, 2008). The reliability and availability of electricity in distribution network is measured based on number of interruptions or outages and restoration time of supply (Eskom. 2012). It is important to balance between the investment cost and network performance by including reliability criteria of distribution networks (Abiri-Jahromi et al, 2012). To improve reliability, the numbers of unplanned outages must be reduced, and the duration of such outages must be shorter. Frequent power interruptions lead to loss of production in the manufacturing sector. In industries and commercial enterprises, poor supply affects productivity and service delivery, which in turn reduces the revenue generated. Long down time of electricity supply lead to losses of perishable items by domestic users. At the commencement of the research, the 22 kV overhead line at location A had large number of defects which required large amount of human and financial resources for its maintenance.

System Average Interruption Frequency Index (SAIFI) is the Key Performance Indicator (KPI) for measuring the frequency of outages while System Average Interruption Duration index (SAIDI) is the KPI to measure the average yearly outage time (Carter-Brown et al, 2008). The Reticulation Supply Loss Index (RSLI) is used to measure the customer hour losses on MV distribution network (NRS 048-6). According to the SAIDI and SAIFI report, the 22KV feeder in location A is the most significant contributor to the poor performance in area B of Province C. The weekly restoration report shows that it takes technicians unacceptably long durations to restore supply. Conversely, the maximum allowable downtime by power utility standards is three and half hours. The excessive downtime is a function of the long hours spent on fault finding and actual repairs of such faults. The control officer compiles a detailed daily sequential report that shows the frequency, duration and customer hour losses of power outages and restoration on the electric power network based on SAIFI and SAIDI standards. In order to achieve a better distribution system reliability indices fault management must reduce the number of faults, interruption, customers affected, outage duration (Sumper et al .2005).

The study focused on improving the network management through increasing the level of optimal switching devices on Medium Voltage (MV) power network to improve the operating efficiency of medium voltage overhead line distribution networks that in turn will improve the restoration time and reduce number of customers affected by the interruptions and MVA losses. The optimal numbere and placement of sectionalizing switches in MV radial distribution network correspond to technical, regulatory and economic aspect (Esteban et al, 2010:283). According to Abiri-Jahromi et al (2012), automation was used by distribution utilities as a successful investment strategy to enhance reliability and operation efficiency. Distribution network automation system can trim down outage events and increase system reliability (Dehghani, and Dashit, 2011: 508). With the use of switching devices placement technique, there is a hypothesis to support possible improvement in the restoration time and reduction in customer hour losses on feeder A. The approach adopted generated output results that may be applied to optimize the network performance by reducing interruptions, improving restoration time and reducing customer hour losses on the Medium Voltage (MV) overhead lines. The location for pilot phase optimal switching device placement technique implementation was based largely on daily network events, showing critical indicators for improvement.

2.1. Optimization method

In this research, zone concept optimal switching device placement was utilized to improve the performance of an over-headline distribution network by minimizing the number of customers and Mega Voltage Amperes (MVA) losses by electricity supply interruption. A 22KV overhead line was divided into zones (sections) equipped with intelligent protective devices to achieve the research objective. According to Abiri-Jahromi et al., (2012: 362), there is a critical need for balance between investment cost and network performance by including specific reliability criteria for equipment idleness, loading level and customer per network. It is important to equip the line with the right automation system to minimize interruption that will lead to improvement on the performance. Preliminary studies of past works on Medium Voltage (MV) overhead lines optimization were reviewed, in order to come up with approaches for switching devices placement to enhance the performance of feeder A 22 KV network. Furthermore, zone concept optimal switching device placement techniques was studied and adopted as a measure for developing a suitable model for optimising the performance of MV overhead line distribution network of the r 22KV power feeder by dividing the network into zones. According to Thomas (2014), determining the optimal number and placement of switching devices within sections of MV overhead line radial distribution network is in correspondence with technical, regulatory and economic aspects. Planning criteria on distribution network is based on analysis of feeder characteristics, existing network performance and experienced based rules (Carter-Brown et al, 2008). The main aim of the study was to deploy optimal switching devices placement technique that will enhance the performance of medium voltage overhead line distribution network by reducing number of customers and MVA losses caused by electricity supply interruption which in return improves the reliability of electricity supply to customers. To assess the reliability of distribution systems, it is important to understand the impact of each supply interruption, outage duration and frequency of occurrence on reliability assessment. The paper discussion is centred on the deployment of zone concept optimal switching devices placement, which are reclosers position on deferent zones of A 22KV overhead line distribution network. Abiri-Jahromi et al., (2012: 363) found that, automated switching devices can reduce the duration and number of customers affected by interruption during transient fault by its fast restoration feature.

2.2. Distribution network automation

In this research, each zone of A 22 KV distribution network is equipped with its recloser to minimize the interrupted area. According to Khan (2015), the placement of protection devices in radial distribution feeder improves network reliability and minimizes the values of reliability indices. Protective devices and switches play important role in reliability of electrical distribution network by minimizing impact of interruption on customers affected and MVA losses (Sohn et al., 2006:941). Billington and Jonnavithula (1996) applied sectionalising switches in primary distribution systems for different applications for reliability improvement, isolation, configuration management and to reconfigure networks. Switching devices selection and cost associated with installations are important in determining the number of distribution automation systems (Billington and Jonnavithula, 1996). In the past, utilities used past experiences, customer data and similar consideration to optimize performance (Billington and Jonnavithula, 1996). However, El-Wafa et al (2002) considered outages, maintenance and investment cost in section of sectionalizing devices placement and number required to optimize the performance.

Auto-reclosers situated closer and behind the faulty part of systems operates to isolate typical faults. Selection switching device is important on automated distribution network, where sectionalising switches are remotely controlled (Billington and Jonnavithula, 1996). Pole Mounted Breakers (PMB) also known as reclosers, sense and interrupt 'fault current' and automatically restore electricity supply after momentary outages. According to the power system philosophy, PMB's isolate faulty distribution network ahead of their position. This equipment automatically isolates faulty part distribution networks ahead of them and report back the change of status and fault information to the control centre (Billington and Jonnavithula, 1996). The breaker are remotely controlled and monitored by the control officer using a control system architecture called Supervisory Control and Data Acquisition (SCADA) for monitoring the continuity of supply to customers and these advanced automation systems are equipped with fault location detection systems (Schneider electricity, 2013).

3. METHODOLOGY

3.1. Zone concept

In the utility company where the study was conducted, power system zone concept was used to divide electricity power networks into zones, separated by intelligent components which include remote controlled reclosers, automatic Sectionalizes, fault path indicators and other methods to handle fault in an optimal technique (Eskom. 2016). The principle of zone concept is to minimize the area affected during power interruptions. Each zone should be equipped with communication for transfer of status indications, measurements, and control commands as required by the secondary distribution application.

3.2. Process of switching device placement selection

It is necessary to position the circuit breakers on the right locations within the distribution network in order for the breakers to optimally serve their required functions. The exposure of unplanned interruptions, and the impact of reliability Key Performance Indicators (KPIs), need to be determined first. In the process of determining the locations for placing circuit breakers, the network length beyond each protective device and the percentage of customers affected by the interruptions were first measured. When the breaker trips, the percentage of the feeder impacted KPI is usually determined based on the zone affected (Leci et al. 2007). It is important to calculate the possibilities of improvement before allocation of each circuit breaker. If no improvement is established, the circuit breakers need to be repositioned to spots where they will serve the desired objectives. Figure 1 shows the decision making process of switching device allocation, while the process of optimization is shown in figure 2.

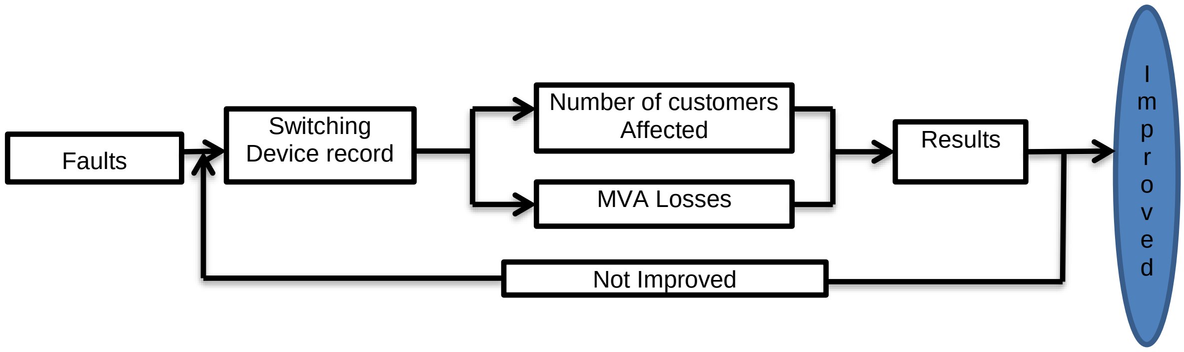

Figure 1: Process of switching device allocation decision

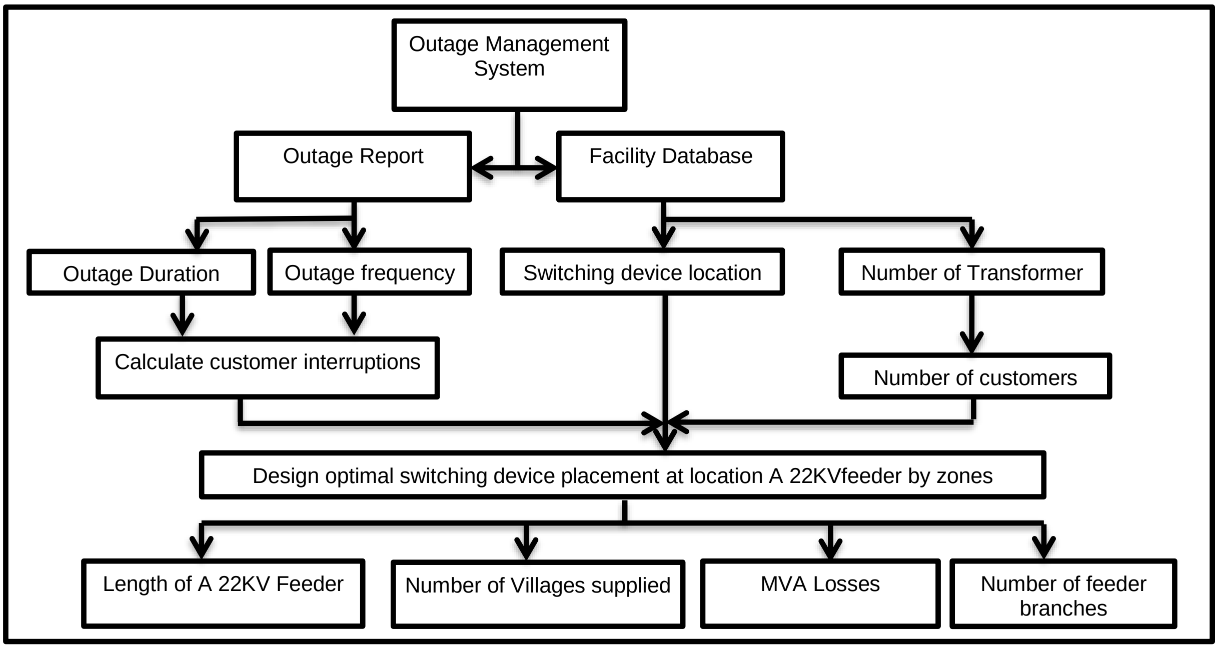

Figure 2: Optimal switching device placement selection process

The process of optimization started by identifying the gaps in the performance of the feeder A 22KV Medium Voltage (MV) line. Outage management system (OMS) was consulted to check the contributors to the poor performance of the MV overhead line distribution network. The OMS provided the outage report and facility database that contained detailed information about interruptions frequency, duration, switching devices interruptions and customers connected per transformer. In the process of designing the optimal switching device placement model, the number of areas, customers, length of distribution network, power losses (MVA loss) and number of feeder branches were considered.

After the optimization process, comparison of results was carried out based on data obtained from both the historical data and that of pilot phase of implementation. The comparison of both historical and pilot phase implementation data was validated through improvement on the reliability indices which includes System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), customer base impact index (CBII) and MVA base impact index (MVABII) for location A 22KV feeder.

Feeder A 22KV overhead line zone concept

Due to the length and complexity of the 22KV feeder distribution network especially in the rural villages, determination of the location where faults originates from is a huge challenge. It is highly important to divide this network into zones and subzones, in order to determine the faulty section (area where the faults come from). Dividing the distribution network into zones and subzones helps in minimizing the number of customers affected by interruptions, improves fault finding time, and reduces restoration time thereby reducing electricity supply losses which is in line with the proposition of Khan (2014). In this study, the sequence on figure 2 was followed to achieve effective zone divisions, but subzones were not considered in this stage of the research because it was a pilot implementation phase. In the optimization process, the overhead line length, number of branches, number of customers, and MVA losses were considered. The switching placement process commenced from the network phase as illustrated on figure 3.

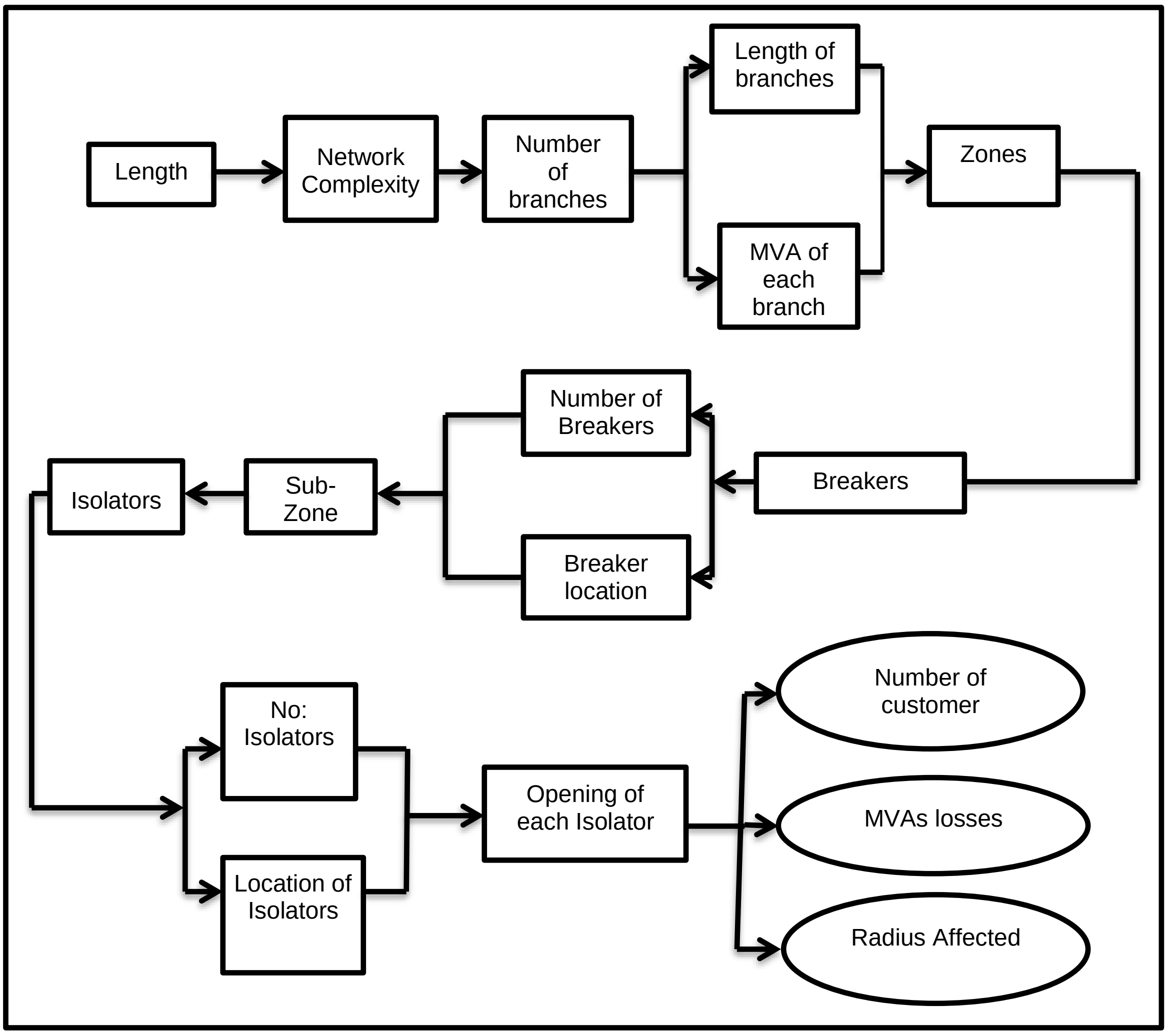

Figure 3: Zone process

Dividing Feeder A 22KV MV overhead lines distribution network into zones, the customer base impact index (CBII) and MVA base impact index (MVABII) need to be considered. The CBII is the ratio of the customer base impacted by the interruption from the total customer base. The MVABII is ratio of MVA base impacted over the total MVA base and can be converted into percentages. They are mathematically expressed as:

Customer Base Impact Index = CBII

$$CBII = \frac{Customer\ base\ impacted}{Total\ MVA\ base} \quad (1)$$

MVA Base Impacted Index (MVABII)

$$MVABII = \frac{MVA\ base\ Impacted}{Total\ MVA\ base} \quad (2)$$

4. RESULT AND DISCUSSION

4.1 Recloser positioning for optimization

It is important to equip the 22KV feeder with adequate protective devices (reclosers) to prevent the occurrence of unnecessary outage duration, minimize number of customers impacted by interruption and minimize Mega

Voltage Amperes (MVA) losses caused by supply interruption. The recloser installed at each zone, validates the direction of fault to technicians and it also minimizes the area impacted by power outages. The Researcher found that, this method minimized the fault finding time by validating possible direction of faults. Recloser positioning technique designed in figure 4 was used to achieve the research objectives. Figure shows the application of switching device allocation in the 22 KV feeder applicable to this research.

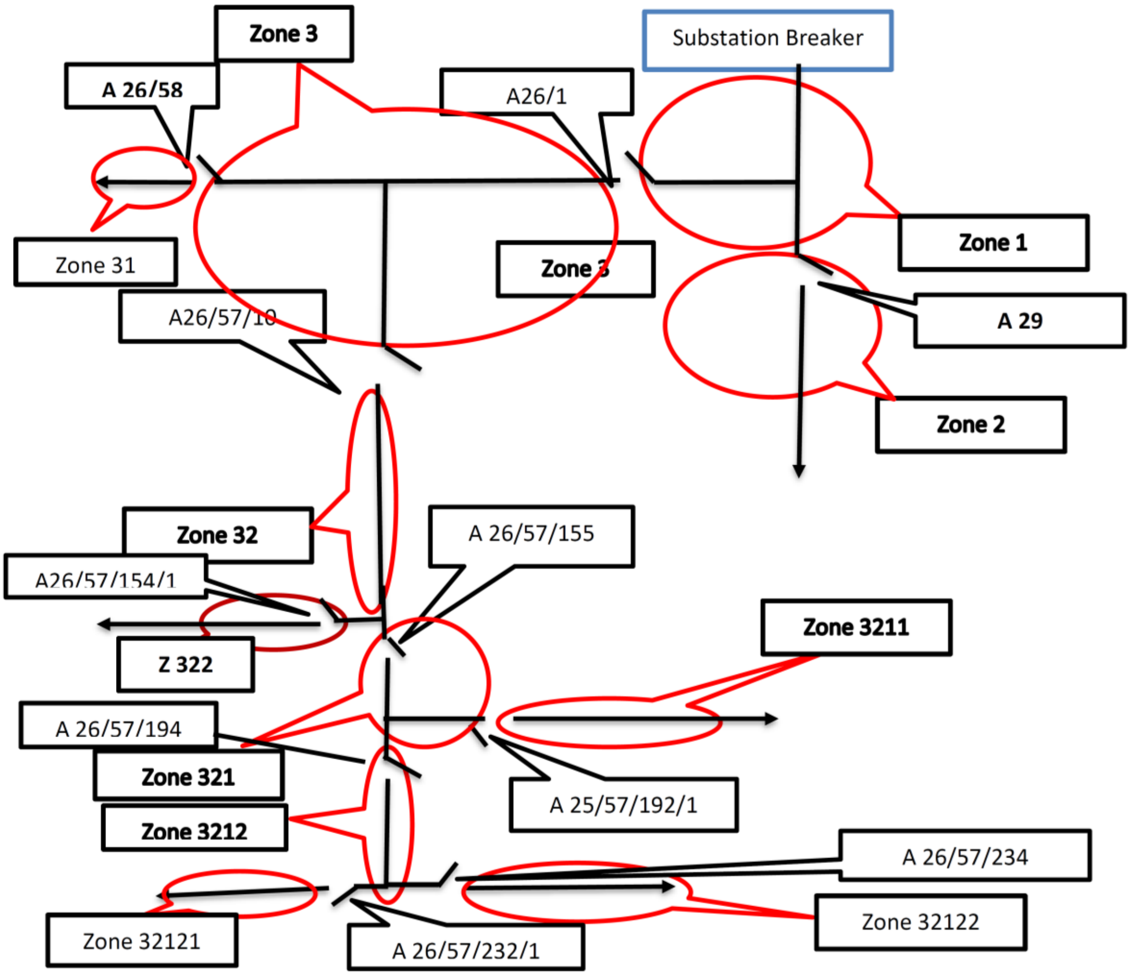

Figure 4: Zone division method

4.2 Recommended length of network beyond the circuit breaker

The recommended distribution network length refers to both backbone (Main line) and / or T-offs (branches and sub-branches of the line). In the process of circuit breaker positioning, the following factors were considered:

- Time taken from the breaker to the closest sectionalising links on fault finding process.
- Fault finding time (Sectionalising time).
- The distance from the recloser to the sectionalising links.
- Number of T-offs (Line branches).

Other factors considered include:

- Dispatching time.
- Time taken to travel from utility offices to site.

The length of the distribution network has significant effect on the fault finding and restoration times. Long and complex line designs with multiple branches requires more time and resources to find the fault location. Faults are dispatched by the Resource management Centre (RMC) to technician. The fault validation process in this research started from the dispatching phase as illustrated in Figure 5 The fault finding process approach adopted is as shown in figure 5.

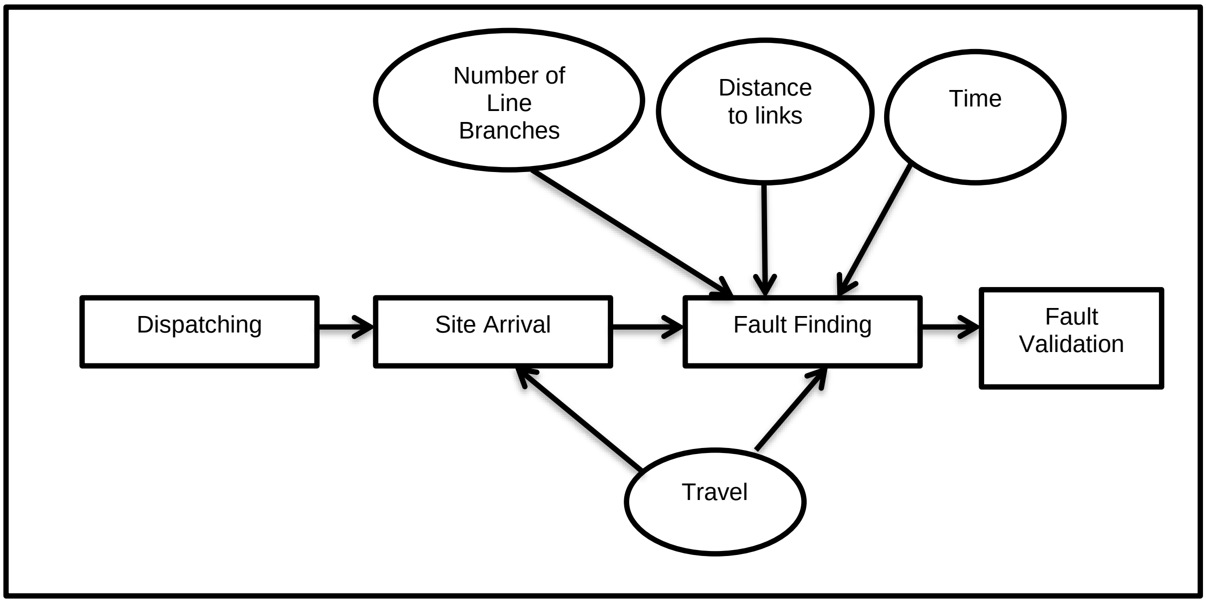

Figure 5: Fault finding process

Recommended MVA of the network beyond the breaker

The recommended MVA of the network refers to the load size. When selecting the location of breakers using the MVA, the following need to be considered:

- Number of transformers and their sizes.
- Number of customers connected to the source.

On the MVA hour loss, the study focused on the number of transformers affected by the opening of each circuit breaker. In this regard, it was important to reduce number of transformers affected by the supply interruption and the outage duration to improve MVA Base impact index (MVABII). The tripping of circuit breakers before optimization affected large number of customers of different villages and farms. The numbers of customers, outage duration are relatively proportional to power losses. The reduction in the number of customers affected, outage duration and MVA loss lead to improvement in the performance which in turn validate the correct positioning of switching device placement. The diagram in figure 6 shows how to determine MVA hour losses.

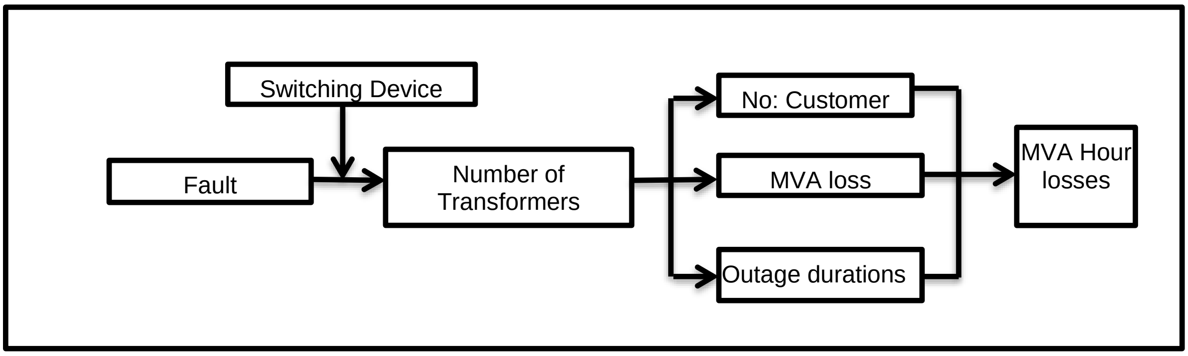

Figure 6: MVA hour losses

The improvement of optimization is mathematically determined by calculating the change on the percentage of MVA losses and number of customers affected before and after optimization. Feeder A 22KV feeder was divided into fourteen (14) zones represented by alphabets (A,B,C,…) in column 1 of table 1. The Zones were divided based on the number of customers, line branches, network length and MVA's of transformers connected. The positioning of intelligent protective devices (remote controlled reclosers) on feeder A 22 KV distribution network determined where the zone starts and ends. The occurrence of fault on each section of the line triggers the reclose behind that fault to trip and isolate only that faulty section of the line. The occurrence of fault on that zone, impact certain number of customers and its MVA losses specified in table 1.

The results obtained by comparative analysis of data on zones, before and after optimization of location A "22KV feeder", is presented using histograms, based on data obtained by measuring the level of improvement of Mega Voltage Ampere (MVA) and by evaluating the total number of customers affected by power supply interruptions. Table 1 shows MVA and the number of customers affected by interruption before and after optimization within various zones.

Table 1: Data representing improvement based on comparison of the status before and after a pilot implementation phase.

Table 1: An example of a clear table

Zone representation	Zone	No. of customers impacted by interruptions before optimization	No. of customers impacted by interruptions after optimization	MVA losses before optimization	MVA losses after optimization
A	1	2867	2867	10.245	10.245
B	2	2867	35	10.245	2.857
C	3	2867	2867	10.245	10.245
D	31	2830	2830	7.238	7.238
E	311	2830	2830	7.238	7.238
F	312	2830	2830	7.238	7.238
G	3121	2808	2808	5.438	5.438
H	3122	2787	2787	4.697	4.697
I	31221	2787	2787	4.697	4.697
J	312211	1365	1365	2.316	2.316
K	31222	2787	880	4.697	1.435
L	312221	2787	601	4.697	0.982
M	312222	2787	279	4.697	0.453
N	3123	2787	542	4.697	0.946

The average number of customers affected by the fault at each zone was used to measure the improvement that the method contributed to switching device placement solutions. Referring to table 1, the average number of customers affected per zone were obtained through mathematical computation, using standard empirical steps. MVA losses 1 represent before state while MVA losses 2 represent the losses recorded after the optimization process. Also, "number of customers impacted 1" represent the total number of customers within each zone affected by interruptions before the optimization while "number of customers impacted 2" are those affected after the pilot phase of the optimization process.

The Average MVA loss before and after optimization was mathematically calculated as shown in figure 7:

$MVA_{avg} = \frac{Total\ MVA\ of\ each\ zone}{Number\ of\ Zones}$................(3) Where MVA_{avg} = Average Mega Voltage Ampere

Before

$MVA_{avg} = \frac{88.385}{14}$ $\quad MVA_{avg}\, before = \mathbf{6.313\ MVA}$

After

$MVA_{avg} = \frac{Total\ MVA\ of\ each\ zone}{Number\ of\ Zones}$ $\quad MVA_{avg}\, after = \frac{66.025}{14}$

$MVA_{avg} = \mathbf{4.716\ MVA}$

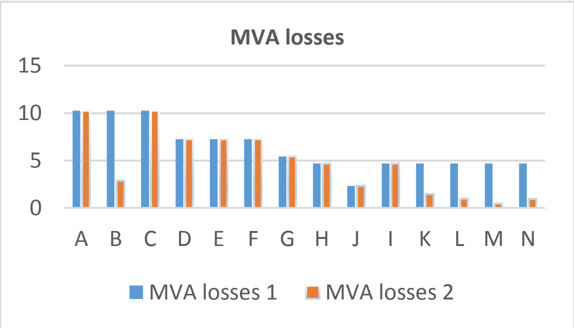

Figure 7: Comparison of MVA losses before and after optimization

% reduction in MVA losses = $\frac{MVA\ losses\ (6.313\ -4.716)}{MVA\ losses\ (6.313)} x100 = \mathbf{25.30}\%$

The average number of customers affected per zone was mathematically determined as shown in figure 8:

$Customers_{avg} = \frac{Total\ number\ of\ customers\ of\ each\ Zone}{Number\ of\ Zones}$ .. (4) Where $Customers_{avg}$ = Average no. of customers

Before

$Customers_{avg} = \frac{37986}{14}$ $Customers_{avg} = \mathbf{2713\ customers}$

After

$Customers_{avg} = \frac{Total\ number\ of\ customers\ of\ each\ Zone}{Number\ of\ Zones}$

$Customers_{avg} = \frac{26308}{14}$ $Customers_{avg} = \mathbf{1879\ customers}$

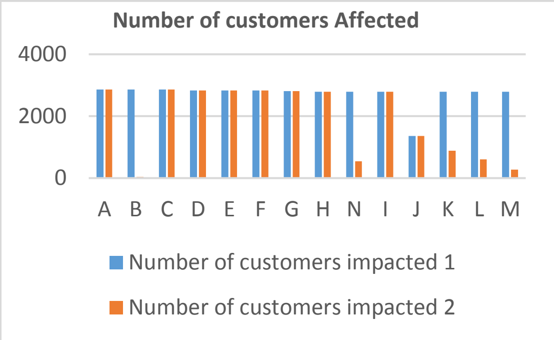

Figure 8: Comparison of number of customers affected before and after optimization

% reduction in no. of customers affected by interruptions= $\frac{No.of\ customers\ affected\ (before-after)}{No.of\ customers\ affected\ before} x100 = 30.74\%$

5. CONCLUSION AND RECOMMENDATION

Switching device placement optimization approach significantly improved the performance of location A 22 KV feeder by reducing the MVA losses and the number of customers impacted by electricity supply interruptions. The value of MVA losses and number of customers affected by electricity supply interruption decreased by 30.74% and 25.30% respectively. Due too high cost of Medium Voltage (MV) isolation equipment, optimization of MV networks is rarely considered within the lifecycle of equipment's but he application of autoreclosers as means of improving the entire system output have proven successful not only in terms of reduction in MVA losses but by providing improved services to end customers. As a recommendation for future research, complete cost models may be explored whereby the losses associated with financial revenue before and after a new model is implemented may be compared putting into consideration the equipment lifespan. The developed model in this research can undergo further improvement and may form part of what will be considered when designing new MV power distribution networks under stringent budget and financial constraints.

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