Applying simplified network feeder reliability modelling as basis for pragmatic strategic management decision making regarding capital and operational investments – a large scale application case study for Eskom Distribution.

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Abstract

This paper provides an overview of how practical but simplified reliability modelling and the resultant quantified relationship between improvements in network performance and related cost can be used to inform strategic and tactical engineering management decision-making regarding capital and operational investment prioritisation on a large scale medium voltage (MV) feeder network. The paper also illustrates that this approach can be applied on smaller areas such as development planning or municipal areas. A summary of the approach is provided, with specific illustrative applications in the context of capital and operational strategic engineering management investment decisions.

1. Introduction

In any large, capital intensive and geographically distributed electrical utility it is a strategic and tactical engineering management decision making challenge to ensure that scarce resources (such as capital and technical skills) are allocated optimally in order to achieve the most effective outcomes from a planning and operational performance point of view.

This paper focuses on illustrating the application of a simplified reliability centred approach to inform strategic and tactical engineering management decision making for a large scale electrical medium voltage feeder network.

The paper is structured as follows: the approach applied for development of simplified reliability modelling decision information tool, the decision framework developed, followed by more detail on example strategic and tactical questions on an illustrative system. The final section concludes with suggestions for future refinements.

2. Approach followed

This paper builds on research work conducted for Eskom Distribution over the period 2008 to 2010 and elements of which were described in previous papers (refer to [1] and [2]). A brief descriptive summary of the approach to construct the simplified reliability modelling on a medium voltage (MV) feeder network and applied in a decision information tool (MS Excel) is provided and illustrated by Figure 1.

Figure 1: Summary of approach
For more detail on steps 1 to 5 refer to [1] and [2]. The starting point for the simplified reliability modelling framework is the PowerFactory results obtained at the end of step 6. These were analysed to determine whether there is a relationship between the feeder characteristics, categorisation and the modelled reliability.

This analysis was followed by a first principle approach to determine the relationship between a feeder’s reliability and:

a) the categorisation of a feeder and
b) the number of components on a feeder.

Then a SAIFI¹ algorithm was developed as the starting point since failures (therefore failure rates) determine interruptions.

The following network component information was applied in the algorithms:

<table>
<thead>
<tr>
<th>Component</th>
<th>Algebraic Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>#TrfsFDI</td>
<td>No. MV/LV transformers on feeder</td>
</tr>
<tr>
<td>#LLFDI</td>
<td>Total MV line length [km]</td>
</tr>
<tr>
<td>#FusesFDI</td>
<td>No. MV fuses on feeder</td>
</tr>
<tr>
<td>#DiscsFDI</td>
<td>No. MV isolators on feeder</td>
</tr>
<tr>
<td>#BrksFDI</td>
<td>No. MV reclosers &amp; sub breaker</td>
</tr>
<tr>
<td>#CustAffected</td>
<td>No. customers interrupted</td>
</tr>
<tr>
<td>#CustTotal</td>
<td>No. customers supplied on feeder</td>
</tr>
</tbody>
</table>

Failure rates for the following network components were applied based on the research detailed in [1] and [2]:

- MV/LV Transformer failure rate: $FR_T$
- MV Line failure rate: $FR_L$
- MV Fuse failure rate: $FR_F$
- MV Breaker failure rate: $FR_B$
- MV Isolator failure rate: $FR_I$

A systematic approach was followed to derive the simplified approach. Two major simplifications that needed to be made are:

a) All protection devices were ignored.
b) Assumption of homogenous distribution of equipment and customers on feeder.

From the analysis the number of components on the feeder is known, but no further information is known regarding the configuration of the network, e.g. the number of customers affected by each breaker trip or the relative location of components on the network. To overcome this problem, a homogenous model is considered. The assumption is made that all components and all customers are distributed homogenously beyond all reclosers (and reclosers are also homogenously distributed on the network). Therefore the following further assumptions are then applied:

i) the number of transformers between the substation breaker and the first recloser is assumed to be $\frac{#BrksFDI}{#TrfsFDI}$, and
ii) the number of customers affected for any single recloser that trips is $\frac{#CustTotal}{#BrksFDI}$.

The equation applied in the model for SAIFI is then:

$$SAIFI = \frac{#FaultsFDI \times #CustAffected}{#CustTotal}$$  \hspace{1cm} (Eq. 1)

Furthermore the following permutations of network configurations in terms of reclosers and fuses were considered:

- Feeders with no reclosers but fuses
- Feeders with reclosers but no fuses
- Feeders with no reclosers but fuses
- Feeders with distribution automation

Finally two types of simplified network configurations (as illustrated in Figure 2) are considered to determine the effect of reclosers on SAIFI.

![Figure 2: Types of network configurations for networks with reclosers](image)

**Type A:** represents a network were all reclosers are installed in parallel with each other. If any recloser opens/trips, supply to all other reclosers will remain intact. The equation applied for SAIFI in this instance is:

$$SAIFI = \left(\frac{2 \times #BrksFDI}{#TrfsFDI} - 1\right) \times Z + \left(\frac{#BrksFDI}{#FusesFDI} \times FR_T\right)$$  \hspace{1cm} (Eq. 2)

**Type B:** represents a number of reclosers in series on the backbone, which means that supply to all downstream reclosers will be lost if any recloser trips (except the recloser furthest from the substation). The equation applied for SAIFI in this instance is:

$$SAIFI = \left(\frac{2 \times #BrksFDI}{#TrfsFDI} - 1\right) \times Z + \left(\frac{#BrksFDI}{#TrfsFDI} \times FR_T\right)$$  \hspace{1cm} (Eq. 3)

**Distribution automation (DA):**

$$SAIFI = \left(\frac{#BrksFDI}{#TrfsFDI} \times FR_T\right) + \left(\frac{#BrksFDI}{#TrfsFDI} \times FR_T\right) \times Z$$  \hspace{1cm} (Eq. 4)

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¹ System Average Interruption Frequency Index (SAIFI) is a measure of how often a customer would experience sustained interruptions on average for a measurement period, typically a supply period of a year. SAIFI can be calculated as:

$$SAIFI = \frac{\sum \text{Customer Interruptions}}{\text{Total Connected Customers Served}}$$

expressed as hours per year.
In addition to the main assumption of homogenous customer and component distributions on a network the following additional assumptions were needed for distribution automation:

i) A back-feed point either exists, or there is a feeder close by from which a back-feed point can be constructed;

ii) All feeder load, beside the load on the section on which the fault occurred, can be supplied by the back-feed under fault conditions, i.e. Type B networks were considered (see Figure 2 B));

iii) Only the customers on the section of line where the fault occurred will be interrupted, while all other load will be supplied by either the substation or the back-feed point.

For all the above equations

\[ Z = \#LL_{FD} \times FR_L + \#Fuses_{FD} \times FR_F + \#Discs_{FD} \times FR_B + \#Brkrs_{FD} \times FR_B \]

It is import to note that network configurations are often a mixture between the Type A and Type B networks.

The equations derived were then applied in the form of a Simplified Reliability Estimation per Feeder (SREF) model to calculate estimates of SAIFI, SAIDI and RSLI for the 229 feeders contained in the sample set of feeders.

\[ Z \]

\[ \text{R² (RHS)} \]

\[ \text{MSEN (LHS)} \]

\[ \text{Type A} \]

\[ \text{Type B} \]

\[ \text{Type A&B} \]

\[ \text{0.70} \]

\[ \text{0.75} \]

\[ \text{0.80} \]

\[ \text{0.85} \]

\[ \text{0.90} \]

\[ \text{0.95} \]

\[ \text{1.00} \]

\[ \text{Normalised MSE} \]

\[ \text{R²} \]

\[ \text{Statistical comparison} \]

\[ \text{Normalised MSE and R²} \]

\[ \text{Statistical outcomes} - \text{SAIFI estimation for Type A, B and AB equations} \]

The DigiSILENT© PowerFactory\(^2\) results of all feeders modelled as part of the reliability modelling performed were then statistically compared with the estimated reliability obtained from the SREF model.

Type A network results had the lowest mean square error (MSE). While the combination equation of both Type A and Type B yielded a coefficient of determination (R\(^2\)) of 0.88 (explaining 88% of the variance between SREF modelled outcomes and Powerfactory results), due to lack of easily obtainable information regarding specific mixes of configurations on individual feeders in the network, the closeness of the statistical fits between Type A and B equations and in order to keep the model less complex it was decided to apply only the Type A equation (Eq.2). The statistical analysis for the Type A equation found that:

The coefficient of determination (R\(^2\)): for the equation for the SREF estimates have a relatively strong relationship with the Powerfactory modelled results and indicated that 71.6% of the variance in the Powerfactory modelled results can be explained by the SREF estimates.

a) F-test for statistical significance: The confidence level that the relationship is statistically significant of 96.7%.

b) Mean squared error (MSE): The MSE is a measure of accuracy for estimation purposes and was the lowest of the three equations (Type A, B and combination A+B) tested.

The impact of the sub-transmission network on the MV feeders’ network performance was also modelled in a simplified way and incorporated into the model as well (this aspect of the modelling is however not discussed in more detail in this paper due to space and time limitations).

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\(^2\) DigiSILENT© (Digital SimuLator for Electrical Network) PowerFactory is an integrated power system analysis tool that combines reliable and flexible system. See http://www.digsilent.de
The SREF results need to be viewed in the context of the aim of the initiative, namely the Pareto principle. For less than 20% of the effort compared to constructing detailed PowerFactory models for the more than 6,800 individual MV feeders in the Eskom Distribution network, currently a more than 70% accurate answer can be obtained with the SREF approach.

From the SAIFI algorithm development the SAIDI\(^3\) and RSLI\(^4\) algorithms were then derived, since causality runs from SAIFI to SAIDI and RSLI (i.e. SAIDI and RSLI will not happen without an event).

In order to address the requirements to answer strategic and tactical questions further developments were then added to the algorithms to accommodate operational and infrastructure intervention modelling, after which all was coded in a Microsoft Excel \(^\text{©}\) (Version 2007, 2010) interface.\(^7\)

The simplified reliability estimation model as implemented in Excel was then applied to inform some strategic questions, examples of which are discussed in the next section.

3. Application for strategic engineering management investment decision-making

The basic principle underlying this approach is that of comparison of realistic “Design” (adjusted for operational environment) expected performance relative to actual “Operational” performance – on a national system level (for the modelled sub-set of MV feeders).

The approach developed is generic in nature and can be applied in any electrical distribution utility with only a modest investment in terms of resources and with limited technical information as explained in the previous section.

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\(^3\) System Average Interruption Duration Index (SAIDI) is a measure of how long a customer would experience sustained interruptions on average for a measurement period, typically a supply period of a year. SAIDI can be calculated as:

\[
\text{SAIDI} = \frac{\sum \text{Customer Interruption Durations}}{\text{Total Connected customers Served}}
\]

expressed as hours per year.

\(^4\) Reticulation Supply Loss Index (RSLI) is a measure of how long the capacity of the system on average was interrupted for a measurement period, typically a supply period of a year. RSLI can be calculated as:

\[
\text{RSLI} = \frac{\sum \text{kVA hours lost}}{\text{Total Connected kVA Served}}
\]

expressed as hours per month.

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Figure 5[A] provides an explanation of the fundamental approach applied in terms of the modelled performance per feeder versus actual reported performance. The chart illustratively shows the expected level of performance [A1] based on the modelling approach developed and explained in the previous section. Some feeders will have reported performances close to the modelled performance and some will be further off from the expected performance. In Figure 5[A] the level where feeders are more than 2 x expected performance (or 100% more) is indicated by the yellow (dotted) line [A2] and where feeders are more than 3 x expected performance (or 200% more) it is indicated by the red (dashed) line [A3].

The approach therefore focuses on identifying feeders that are significantly off [A4] from the expected performance levels in terms of the specific network performance indicator (e.g. SAIDI or SAIFI). To further illustrate the concept Figure 5[B] provides a quantitative picture of such outliers identified (in Figure 5[A] [4] = [4] and [5] in Figure 5[B]).
In practice one needs to focus on feeders that are major contributors to system level performance. Therefore the approach includes evaluating the contribution of an individual feeder to the overall system level performance indicator (illustrated in [B6]).

Lastly, in order to achieve focus on the feeders that are performing far off from what their designed expected performance indicate, only feeders are selected that are significant contributors to specific indicators as well as being far off in terms of BOTH SAIDI and SAIFI (illustrated in [B7]).

Subsequently a “Performance” and “Design” filter and focus concept and process was developed as illustrated in Figure 6.

First, an explanation of the colour key is required after which the process is explained. For reference purposes in this paper numbers (i–vi) are associated with the colour key from the illustration in Figure 6.

- (Type i) – these feeders are NOT major contributors to SAIDI and are ignored by the process (or filtered out at the start of the process).
- (Type ii) – these feeders have basic data concerns that first need to be addressed before they can be included in the modelling system.
- (Type iii) – these feeders ARE major contributors to SAIDI.
- (Type iv) - MAJOR SAIDI contributors and outliers in terms of both expected designed SAIDI and SAIFI performance.
- (Type v) - MAJOR SAIDI contributors and not supporting SAIDI regime from design point of view, but in line with expected designed performance for SAIDI and SAIFI.
- (Type vi) – these feeders are a mix of both type (iv) and (v).

Next the process applied in terms of specific filters is explained:

Filter 0: An initial filter around data quality and accuracy was introduced to filter out any feeders (Type ii) for which obvious data issues could be highlighted. These issues need to be addressed before the feeder can be accurately evaluated for expected performance in order to inform on potential actions to be taken for a specific feeder.

Filter 1: Significance in terms of customer interruption hours per annum contribution (type iii). Due to overall strategic focus on reducing SAIDI, this step is (first) applied to test for significance in terms of a feeder’s contribution to customer interruption hours per annum. Exactly what value this parameter is set to depends on the envisaged system level SAIDI performance required.

Filter 2: Deviance from expected modelling SAIDI and SAIFI performance levels.

The next filter applied is that of the deviance of reported feeder performance from expected feeder performance as based on the modelling from this research. In the example a cut-off level of 200% (more than 3 x expected performance as explained in Figure 5 [A]) as applied for both SAIDI and SAIFI. This filter was then split into 3 sub-filters.

Filter 2a: Performance focus filter - aims to flag feeders (Type iv) that are:
(a) Significant in terms of customer hour interruptions contribution.
(b) The reported performance of a feeder is significantly worse than the expected modelled performance for both SAIDI and SAIFI.
(c) Therefore it may require an investigation as to what factors (with a focus from operational and maintenance point of view) could be contributing to the significant difference in performance levels.

Filter 2b: Design focus filter - aims to flag feeders (Type v) that are:
(a) Significant in terms of customer hour interruptions contribution.
(b) The reported performance of a feeder is within acceptable levels around the expected modelled performance for both SAIDI and SAIFI, but has an inherently designed high SAIDI and SAIFI.

Merely focusing on trying to achieve operational performance improvements from these Filter 2b feeders is unlikely to yield significant performance improvements as these feeders are already performing close to expected design levels. These “design” issues would then need to be investigated and potential design changes (capital planning) interventions need to be evaluated in terms of various business measures such as cost-benefit, return on investment, cost-of-un-served energy and others informing decisions on whether to implement design changes or not. Examples of such interventions could include feeder splitting, adding additional sub-stations, introducing back-feeding links as well as network visibility options on selected feeders.

Filter 2a+2b – combination of Filter 2a and 2b – feeders (Type vi) that meet both criteria simultaneously.

These feeders have inherent designed high SAIFIs and SAIDIs, while at the same time having actual performance levels significantly worse than expected performance norms for such feeders. In order to clearly understand the design changes required it is therefore important that operational performance issues are isolated and addressed first to ensure that possible capital interventions (which typically take longer and cost significantly more) do not address symptoms of operational deficiencies but rather actual relevant underlying design causes.

This pragmatic and quantifiable approach was further applied to inform Eskom Distribution strategic and tactical engineering management decision-making to inform on diverse questions (subject to various assumptions) such as:

- What is the expected system performance levels based on the modelled system?
- What are potential investment requirements towards achieving a system SAIDI of for example 1 hour?
- What are the possible implications to the system SAIDI performance levels due to the expansion of the network as a result of a planned additional 1.3 million electrification customers?
- What are the performance implications of reducing the length of typical major SAIDI contributing long MV feeders?

The topics mentioned here are non-exhaustive and serve to illustrate the variety of the type of questions that can be answered with this approach.

An outcome from this study is that the Eskom Distribution business has a pragmatic methodology to generate an empirically based “norm” for expected performance for different types of feeders as well as individual feeders against which reported feeder performance can be compared or “benchmarked” with relatively modest effort.

In the next section a more detailed illustrative example of reducing line lengths for hypothetical feeders in a hypothetical area is discussed.

4. Illustrative example – SAIDI and capital implications of reducing feeder lengths

The SREF model was used and a “what-if” analysis was conducted to inform this question. This was achieved by constructing a scenario in which a substation and line-split intervention for each feeder of total length exceeding 100 kilometres and individually contributing more than 16,500 customer interruption hours was applied. Note that for this illustrative example the filter evaluating actual versus expected performance (Filter 2 from the previous section) was not applied (only the criteria stated above).

The map in Figure 7 shows a set containing 50 11kV-33kV feeders. The group of 50 feeders’ SAIDI illustratively is 55.37.
The following example shows how the model was applied to select feeders based on the following criteria:

a) Feeders in area (black)
b) Where feeder length > 100 km (indicated in red)
c) Where feeder length > 100 km and feeder contributing > 16,500 customer interruption hours per annum (indicated in green)

Based on this length criteria (b) there are 25 (50%) of the feeders that are longer than 100km in length. The average feeder length of the 25 feeders is 366.96 kilometres.

Based on the criteria (c) considering significance in terms of contribution to annual customer hour interruptions there are 14 (28%) of the feeders that are significant SAIDI contributors in addition to being longer than 100 kilometres in length. The average feeder length of these 14 feeders is 401.51 kilometres. The SAIDI for the sub-set of 14 feeders is 64.64 hours per annum.

The long radial nature of these feeders indicates that the probability will be high that a number of these feeders would require a substation intervention to split the feeder. The substation intervention includes 132 kV (High Voltage) line as well as 11 kV or 22 kV (as relevant) line that needs to be constructed to implement the substation and therefore inherently includes a line-split.

As a result of lack of information about exactly where a feeder will be split and how much additional line would be required to construct a split (unless a detailed analysis per individual feeder is conducted), a simplified assumption had to be made. The approach applied was to convert the average investment cost associated with a substation and required line-split intervention to an average investment cost per kilometre of the full feeder line length (at R436,560.00 per km in the example).

Due to the long radial nature of these feeders it was assumed that the full cost of a substation will be attributed to a single feeder while only the improvement on the specific feeder is included in the calculation (although in practice some other feeders may also benefit from the introduction of a substation which will reduce the estimated cost per SAIDI hour improvement per feeder).

This cost per kilometre was then applied to each feeder selected to be split and multiplied by its own length to obtain a investment estimate for each individual feeder.

The impact of the capital intervention on the 14 selected feeders yielded an improvement for the area system of 50 feeders’ SAIDI of 28.5% at a cost estimate of R2.0 billion rand (approximately R144 million rand per feeder) as shown in Figure 8.

The fact that 14 feeders meet the criteria (total length exceeding 100 kilometres and individually contributing more than 16,500 customer interruption hours) does not imply that it makes financial and economic sense to simply apply these interventions to all these feeders. At some point individual feeders will start showing a diminishing return in terms of SAIDI reduction achieved relative to investment required to be spent to achieve this improvement.

The Pareto (80/20) principle was therefore applied to determine the point of diminishing return. The individual feeders’ SAIDI reduction contribution was ranked and the point selected where 80% of the SAIDI reduction possible with the overall initial set of 14 feeders was achieved. The cut-off point obtained in this way was where an individual feeder contributed less than 1.2% to the overall system (50 feeders) SAIDI improvement.

The sub-set set of feeders where subsequently optimised (ranked according to best SAIDI reduction versus costs) as shown in Figure 8.
Evident from the illustration is that an optimised set of feeders can be obtained that delivers 80% of the SAIDI reduction possible (24% improvement = 80% of the overall 28% improvement possible with 14 feeders) for only 59% of the original investment required (R 1.2 billion of R 2.0 billion). The total number of feeders that will be split is 8 of the original 14 selected feeders.

The cost per overall system (50 feeders) SAIDI hour improvement achieved in this way reduced from R128 million per SAIDI hour to R89 million per SAIDI hour (a 31% improvement in rand per SAIDI hour).

5. Shortcomings and further developments

The simplified model has some pertinent shortcomings alluded to such as:

a) Heterogeneous networks assumption
b) Insufficient modelling of the actual fuse philosophy applied (lack of detail available for all feeders)
c) Not modelling non-feeder originated faults completely (faults caused by other parts of the network).

However, further research and analysis providing specific data elements to develop more sophisticated equations in terms of equipment and customer distribution may yield even more accurate outcomes in future. Specifically incorporating the location of equipment and customers on the feeder will contribute greatly to the accuracy of the models.

Even with the current shortcomings this approach is a major step in supporting pro-active strategic and tactical engineering management decision making related to network performance implications versus large capital investment expected costs.

6. Summary and conclusion

The paper has illustrated the application of a simplified reliability centred approach to inform strategic and tactical engineering management decision making. The outcome of this work has produced a pragmatic, simplified and easy to understand engineering technically informed framework for providing insight into expected MV feeder performance levels from both a design and operational perspective.

Although the initial focus was to develop an approach for a large scale electrical medium voltage feeder network, we have also illustrated with a practical example that the approach can also be applied on a small or micro scale (municipal or smaller development planning area) level with relatively modest effort.

The approach can inform on various questions typically posed by strategic and tactical engineering management decision makers.

Finally, the value of this type of approach is to allow proactive informed decision making (with relative ease and low cost) regarding major capital and operational expenditure on MV feeders.

This is achieved by contrasting the implications of such decisions in terms of potential implications for performance of feeders (measured in terms of network performance indicators such as SAIDI, RSLI, CAIDI and SAIFI) relative to expected costs.

7. Acknowledgements

Engineering network modelling:
Johan Coetzee, Johanneke van der Merwe
Concept development & strategic development inputs:
Hendri Geldenhuys, Gerhard Botha, Nelson Nunes, Malcolm van Harte, Theo Kleynhans, Danie Conradie
Data and information support: Hennie Nel

8. References