Simplified reliability modelling as a basis for performance target setting and prioritising electrical power system-level investment

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ABSTRACT

City Power's Engineering Operations performance targets have traditionally been informed through benchmarking with overseas utilities, but this approach to target setting has proven to be inadequate. An alternative approach was therefore considered whereby the performance targets are based on the operationally achievable performance levels of the network, subject to the existing characteristics of the infrastructure and its operations.

Eskom Distribution developed a simplified reliability modelling approach to inform the designed performance level of their networks. This approach was used and applied on the City Power networks. Where necessary, the initial Eskom approach was customised in order to accommodate the differing standard configurations of the City Power networks.

The outcome of this reliability modelling enabled the Engineering Operations division to propose reasonable "expected" SAIDI and SAIFI target ranges for the City Power networks, and facilitated a better understanding of the expected performance of all the networks (feeders and substations) in their area of supply. The outcome of the study was also used to develop network criticality maps, highlighting the networks that significantly contribute to the system SAIDI.

KEYWORDS

Network reliability, performance evaluation, network planning, SAIDI.

1 Introduction

City Power's Engineering Operations network performance targets have historically been informed by performance levels benchmarked relative to overseas utilities. Due to a lack of system-specific performance models and approaches, international (and national) benchmark studies are most often applied in decision-making to inform expected performance levels (and therefore performance targets). Benchmarking outcomes should, however, be applied with caution, as there are some detailed factors that must be considered for comparative decision-making. A fundamental flaw with a benchmarking-based approach is that, generally, benchmarking ignores current network topology and its influence on the inherent performance level capability of the particular distribution system in question [1].

City Power's network topology, customer numbers and distribution on the network, operating environment and other network topology related variables are very different from that of overseas utilities, and hence the "generalised" benchmarking-based approach to target setting has proved to be inadequate for City Power's purposes (as well as other South African utilities such as Eskom [1]). This finding is most probably true for any individual electrical power utility in the world, for there are no "identical" or "representative" networks internationally – only specific networks constructed subject to specific network topology requirements at specific points in time. City Power's Engineering Operations division therefore initiated a study into the designed performance level of the existing network – with specific focus on SAIDI and SAIFI.

The purpose of this study was to inform the operationally achievable performance levels of the network subject to the existing infrastructural and operational characteristics.

2 Approach

As mentioned in the introduction, a different approach was followed for this study whereby the expected performance of a network is modelled, given the specific network topology, customer numbers, operating environment etc.

Several software packages are commercially available for reliability modelling of electrical networks, e.g. PowerFactory, PSS/E, etc. These software packages require detailed network models to model the expected reliability of power networks. City Power network planners use PowerFactory for the modelling of all HV networks, but the City Power MV networks are not yet entered into PowerFactory. Furthermore, PowerFactory is not capable of modelling the reliability of all the different substation configurations typically associated with these networks. Although a high level of accuracy is obtained by modelling with the specific software packages mentioned, significant investment and effort is required to create such models, especially when large utility-scale networks are modelled. Subsequently, an alternative approach had to be considered from a resource and information availability and time perspective.

This project made use of a simplified approach to reliability modelling, developed for Eskom Distribution over the period 2008 to 2012 (refer to [1], [2], [3], [4], [5] and [6]). The approach recognises that, from first principles, certain key network components like length of line, number of transformers, location of fuses and breakers etc. have a significant impact on the reliability of a feeder and/or substation. Reasonable assumptions are made regarding the failure rates, maintenance frequencies, travel times and repair times, specific to the City Power context (considering e.g. differences in high density urban versus less dense rural type environments within the City Power service area), and relevant implications associated with the different components. A key assumption is that the City Power networks are reasonably maintained[1] and operated. The number of components of each type and the relevant assumptions are then used in the simplified approach to calculate the expected downtime experienced by customers supplied on different points of the network.

The outcomes from this approach therefore provide the designed "realistically expected" performance base for the City Power network.

3 Modelling methodology

The reliability modelling was split into two separate modelling steps, i.e.:

(a) Sub-transmission network modelling, including all substations and feeders ≥ 20 kV.

(b) Distribution network modelling, including all feeders ≤ 20 kV.

Both these modelling steps are described in more detail below.

3.1 Sub-transmission modelling methodology

A decoupled approach was used for the modelling of the sub-transmission network (for more detail, refer to [7] and [8]). This approach decouples the contribution of substation events from the sub-transmission line reliability assessment. The point of demarcation between the substation and the sub-transmission lines was defined between the feeder breaker and the line isolator (see Figure 1).

As a first step, a detailed model of the substation is created. A reliability analysis is then performed on this substation and an annual outage frequency and annual outage duration is produced for the downstream busbar of each substation. This is illustrated in Figure 1, where the substation shown in (a) is replaced by the equivalent busbar in (b).

The next step is to generate an equivalent system model by replacing all substations with a busbar, of which the outage frequency and outage duration are equal to those of the substation equivalent. This equivalent system model is then used to calculate the reliability of the overall sub-transmission system.

[1] This assumption may not hold true in all instances, but actual network performance needs to be compared to the "ideal but realistic" expected performance (i.e. factoring in the topographical and environmental realities).

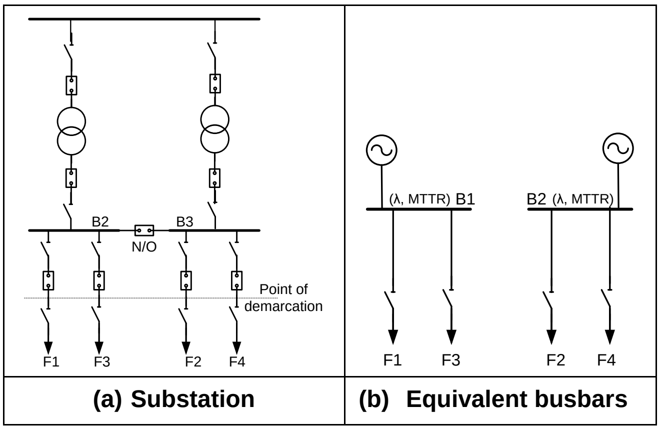

Figure 1: Reducing a substation to a busbar with equivalent unavailability (adapted from [7])

3.1.1 Substation reliability calculation

The substation reliability calculation considers a detailed model of the substation, including the number of components in each substation, how the components are connected (i.e. the configuration), the associated failure rate and repair times of each of the components, and the customers impacted by each failure, as determined by the normal operating conditions and protection philosophies applied on the network. For more detail, refer to [6]. The sub-transmission model makes provision for nine standard busbar configurations, and each of the City Power substation busbars were classified according to these nine standard configurations[2].

Planned maintenance requirements were also considered when calculating the total outage duration experienced by the customer.

3.1.2 Sub-transmission line reliability calculation

Failures of the line and the line isolators were considered for the sub-transmission line calculation. The annual downtime experienced by a customer supplied from a radial network is calculated using the following equation:

$$U_{line} = [(\lambda_{line} \times LL) \times (T_{Dispatch} + T_{Travel} + T_{Switch} + R_{line})] + [(2 \times \lambda_{isolator}) \times (T_{Dispatch} + T_{Travel} + T_{Switch} + R_{isolator})]$$

Equation 1

[2] If the actual busbar configuration did not correspond with any of the standard configurations, then the busbar was classified as the busbar type that corresponds most closely to the reliability measure of the actual configuration.

Where:

- U_{line} : *Outage duration (per annum) of the line/cable module (h/a)*
- λ_{line} : *Failure rate of the line/cable (occ/km/a)*
- LL : *Line length (km)*
- $\lambda_{isolator}$: *Failure rate of the line isolator (occ/a)*
- $T_{Dispatch}$: *Dispatch time (h)*
- T_{Travel} : *Travel time (h)*
- T_{Switch} : *Switching time (h)*
- R_{line} : *Repair time of the line (h)*
- $R_{isolator}$: *Repair time of the isolator (h)*

3.1.3 Sub-transmission network reliability calculation

If overlapping failures are ignored, the total outage duration at a specific busbar is the sum of the outage duration due to substation faults and line faults. This is illustrated by Equation 2.

$$U_{Tx} = U_{substation} + U_{line}$$

Equation 2

Where:

- U_{line} : *Outage duration experienced due to outages on the sub-transmission lines*
- $U_{substation}$: *Outage duration experienced due to outages on the substation equipment*
- U_{Tx} : *Outage duration experienced due to outages on the sub-transmission network*

3.2 Distribution network methodology

This section provides more information on the methodology used to model the distribution network (including all feeders ≤ 20 kV).

3.2.1 Equipment count

The City Power distribution networks consist mainly of two different equipment types, i.e. cables and load centres. Each load centre consists of different components that can fail and result in an outage on a feeder. The following assumptions were made to derive the number of components from the number of load centres:

(a) Each load centre contains an isolator.
(b) Load centres that supply customers also contain a transformer and a fuse.
(c) There are no breakers in the load centres.

Table 1 provides a summarised view of these assumptions.

Table 1: Distribution circuit asset data assumptions

Equipment count	Load centre mapping
# Breakers	0
# Transformers	# Load centres with customers allocated
# Fuses	# Transformers
# Isolators	# Load centres

3.2.2 Failure rates

Reasonable assumptions were made for the equipment failure rates. These assumptions are based on the expectation that the City Power networks are reasonably maintained and operated. Failure rates for lines and cables are assigned per kilometre, with a realisation that a longer line or cable would have a higher exposure to faults.

3.2.3 Cable exposure

In a typical urban electrical network, electric power cables contribute most towards expected annual faults and fault durations due to the high proportion of network constructed using cables.

Cable networks tend to contain a number of sections where more than one cable may be connected in parallel between two nodes (see Figure 2). Parallel cables (denoted by $x_1 \dots x_3$ in Figure 2) are laid in close proximity, or the cables are connected to the same switching device to isolate the cables in parallel. The customers (connected to load centres denoted as LC1…LC4 in Figure 2) are therefore exposed to faults on all parallel sections of the cable. Consider the cable network illustrated in Figure 2. The total length of cable that each customer is exposed to is:

$$Total\ cable\ length = 3 \times x_1 + 2 \times x_2 + x_3$$

Equation 3

Considering an equal equipment distribution (i.e. $x_1 = x_2 = x_3$) Equation 3 simplifies to

$$Total\ cable\ length = 6 \times x_1$$

Equation 4

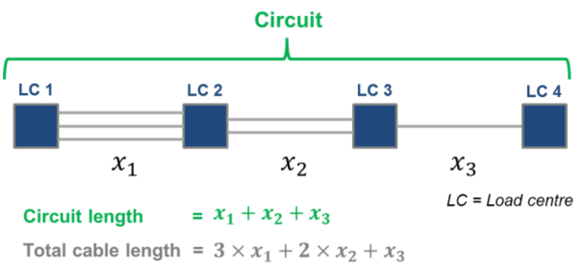

Figure 2: Diagram illustrating cable exposure to common mode failures

3.2.4 Equipment distribution

The simplified reliability modelling approach ignores the actual contribution of customers and equipment along the length of the feeder. An evenly distributed model is considered, which means that all components, e.g. load centres, are distributed homogenously along the length of the feeder and all customers are distributed homogenously beyond all load centres[3].

3.2.5 Outage duration

The total outage duration per fault can be broken down into smaller components, as illustrated in Figure 3. Each of these time components is discussed briefly below.

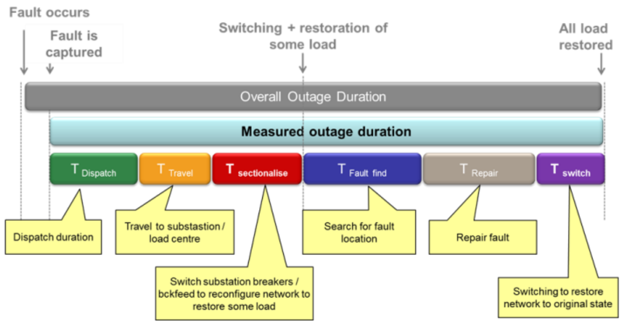

Figure 3: Outage duration components associated with MV feeder outages

Dispatch: This is the (reasonable) duration from the moment the fault is logged in the system (through either a customer call or a signal from a remote terminal unit (RTU) in the substation), until an operator starts travelling to site.

Travel: This is the (reasonable) time required by the operator to drive to the substation. Different times were assumed for different depots, considering factors such as the average travelling distance between the depot and the substations as well as the expected average travelling speed.

Sectionalising: The (reasonable) sectionalising time represents the time required to create open points and/or switch the backfeed point, in order to restore supply to those customers that are not supplied from the faulty part of the network.

Fault find: This is the (reasonable) time required to identify the faulty piece of equipment, i.e. the time that elapses from the moment the

[3] This assumption can be changed if relevant customer distribution and positioning data is available. However, in most cases it is not readily available, hence the need for this approach.

operator arrives on site until he can start with the equipment repair.

Repair: This is the (reasonable) time required to repair/replace the faulty piece of equipment. Different repair times are assumed for different pieces of equipment.

Switch: After the faulty piece of equipment has been repaired/replaced, the network needs to be switched to normal. This time is referred to as the (reasonable) switching time.

The sum of these time components represents the total outage duration experienced by a customer for the full duration of the fault.

3.2.6 Customer restoration factor

Supply can be restored to some of the interrupted customers before the failed component is repaired. The percentage of customers that can be restored depends on the isolating equipment, backfeed-ability and configuration of the network. This percentage is referred to as the "customer restoration factor". The customer restoration factor has no impact on the customers interrupted during the dispatch, travel and sectionalising duration, but it affects the customers interrupted during the fault find, repair and switching duration.

3.2.7 SAIDI and SAIFI algorithm

An algorithm to determine the SAIDI and SAIFI for a specific feeder was derived for both planned and unplanned outages. The algorithms for unplanned outages are discussed next.

The **unplanned SAIFI algorithm** for a feeder with fuses but without reclosers (or similar protection devices), is shown in Equation 5:

$$\boldsymbol{SAIFI_{unpl\_fdr}} = (\boldsymbol{\#Cable} \times \boldsymbol{FR_C} + \boldsymbol{\#Fuses} \times \boldsymbol{FR_F} + \boldsymbol{\#Discs} \times \boldsymbol{FR_D}) + \left(\frac{\boldsymbol{\#Trfrs}}{\boldsymbol{\#Fuses}} \times \boldsymbol{FR_T}\right)$$

Equation 5

Where:

$SAIFI_{unpl\_fdr}$	*: Unplanned SAIFI for a specific feeder*
#Cable	*: Total cable length of feeder (km)*
#Trfrs	*: Number of transformers on feeder*
#Fuses	*: Number of fuses on feeder*
#Discs	*: Number of isolators on feeder*
FR_T	*: Transformer failure rate (occ/a)*
FR_C	*: Cable failure rate (occ/km/a)*
FR_F	*: Fuse failure rate (occ/a)*
FR_D	*: Isolator failure rate (occ/a)*

The **unplanned SAIDI algorithm** is similar to the SAIFI algorithm, but includes the outage duration. The unplanned SAIDI algorithm for a feeder with fuses but without reclosers (or similar protection devices), is shown in Equation 6:

$$SAIDI_{unpl\_fdr} = \left[(\#Cable \times FR_C + \#Fuses \times FR_F + \#Discs \times FR_D) + \left(\frac{\#Trfrs}{\#Fuses} \times FR_T\right)\right] \times T_{response}$$

$$+ \left[(\boldsymbol{\#Cable} \times \boldsymbol{FR_C} \times \boldsymbol{Rtime_C} + \boldsymbol{\#Fuses} \times \boldsymbol{FR_F} \times \boldsymbol{Rtime_F} + \boldsymbol{\#Discs} \times \boldsymbol{FR_D} \times \boldsymbol{Rtime_D}) + \left(\frac{\boldsymbol{\#Trfrs}}{\boldsymbol{\#Fuses}} \times \boldsymbol{FR_T} \times \boldsymbol{Rtime_T}\right)\right] \times (\boldsymbol{1} - \boldsymbol{CRF})$$

Equation 6

Where:

$SAIDI_{unpl\_fdr}$	*: Unplanned SAIDI for a specific feeder*
#Cable	*: Total cable length of feeder (km)*
#Trfrs	*: Number of transformers on feeder*
#Fuses	*: Number of fuses on feeder*
#Discs	*: Number of isolators on feeder*
FR_T	*: Transformer failure rate (occ/a)*
FR_C	*: Cable failure rate (occ/km/a)*
FR_F	*: Fuse failure rate (occ/a)*
FR_D	*: Isolator failure rate (occ/a)*
CRF	*: Customer restoration factor*
$T_{response}$	*: The sum of the dispatch, travel and sectionalising time*
$Rtime_T$	*: The sum of the fault find, transformer repair and switch time*
$Rtime_C$	*: The sum of the fault find, cable repair and switch time*
$Rtime_F$	*: The sum of the fault find, fuse repair and switch time*
$Rtime_D$	*: The sum of the fault find, isolator repair and switch time*

The total outage duration that a customer experiences due to outages on the MV feeder is therefore the sum of the outage durations experienced due to planned and unplanned outages. This is shown in Equation 7.

$$\boldsymbol{U_{Dx}} = \boldsymbol{SAIDI_{unpl\_fdr}} + \boldsymbol{SAIDI_{pl\_fdr}}$$

Equation 7

Where:

$SAIDI_{unpl\_fdr}$	:	*Unplanned SAIDI for a specific feeder*
$SAIDI_{pl\_fdr}$	:	*Planned SAIDI for a specific feeder*
U_{Dx}	:	*Total outage duration experienced due to outages on the MV feeders*

3.3 Total outage duration

The total outage duration experienced by a customer can now be calculated by combining the contribution of both the sub-transmission network and the distribution network. This is illustrated in Equation 8.

$$U_{Total} = U_{Tx} + U_{Dx}$$

Equation 8

Where:

U_{Tx}	:	*Outage duration experienced due to outages on the sub-transmission network (see Equation 2)*
U_{Dx}	:	*Outage duration experienced due to outages on the distribution network (see Equation 7)*
U_{Total}	:	*Total outage duration experienced by a customer*

4 System-level reliability

The approach explained above was used to calculate the "realistically expected" SAIDI and SAIFI of City Power's entire network (depicted in Figure 4); this includes more than 100 substations (373 busbars), 276 station transformers, an installed capacity of more than 10 000 MVA, more than 7 000 km of MV cable, 14 735 load centres and more than 300 000 customers.

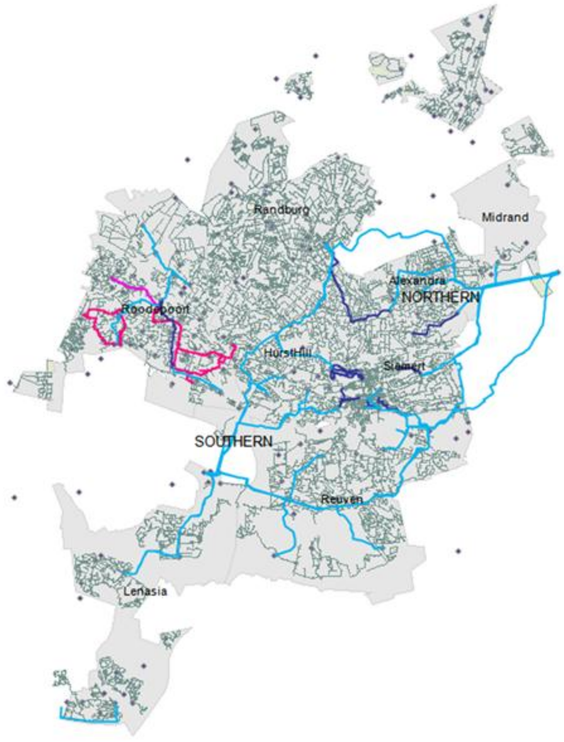

Figure 4: City Power sub-transmission and distribution networks

This expected performance was used to derive the following valuable executive decision support outcomes:

a) Informed setting of network performance targets for the next five years (in terms of relevant measures such as SAIDI, SAIFI etc.).

b) Informed the development of system-level criticality maps to understand which networks are performing worse than expected and where to focus efforts for best "network performance improvement returns".

c) Determine the impact of different performance improvement interventions on the network to assist in the development of an improvement strategy, considering cost and performance improvement trade-offs.

Each of these decision support outcomes is discussed briefly below.

4.1 Setting performance targets

The modelled system target outcomes were used to determine City Power's performance targets for the next financial year. The realistic designed performance was less than the City Power actual performance in 2012/2013, but further investigation and planning is required to improve the performance of those feeders which actual performance is much worse than the realistically expected performance.

City Power therefore considered a phased approach, whereby improvement towards the designed performance level is achieved over a five-year period. For the first round, a simplistic linear improvement from the existing performance levels to the targeted performance levels was used to determine the performance target for each financial year. Such a phased approach is illustrated in Figure 5. A 10% error band is shown, to accommodate any changes in the assumptions and/or corrections of network data.

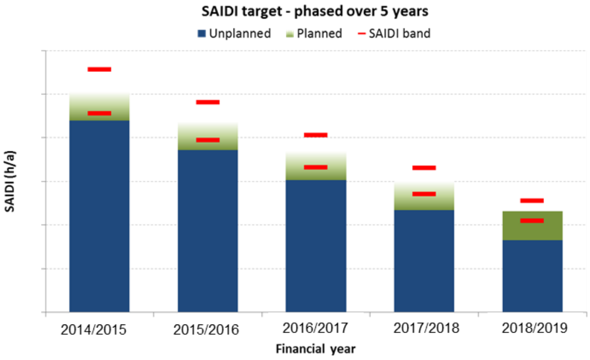

Figure 5: Illustrative SAIDI target for the next five years

4.2 Criticality maps

The actual performance of each individual, modelled feeder was compared to its expected modelled performance. A method of relative comparison was used to flag problematic feeders. Various assumptions were made in the modelling approach and therefore some error was allowed between the actual and expected SAIDI, to allow for differences that could be caused by the modelling assumptions and/or data deficiencies. A feeder was flagged as problematic only if the reported annual SAIDI was more than three times the expected SAIDI. This approach is illustrated in Figure 6.

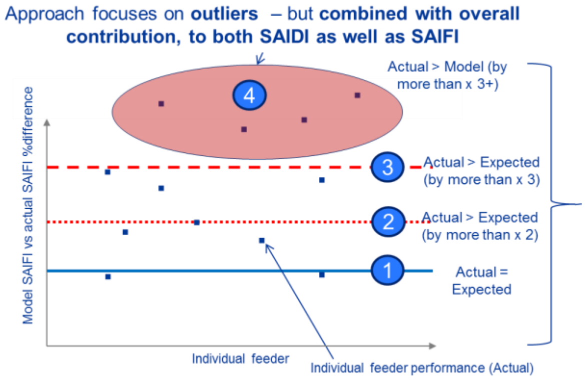

Figure 6: Approach to identify outliers relative to expected performance [5]

All feeders identified through this approach were highlighted spatially and a criticality map (see Figure 7) was developed. It is clear from this map that the problematic feeders are geographically grouped together, highlighting particular geographical areas that require specific focus in order to improve the performance.

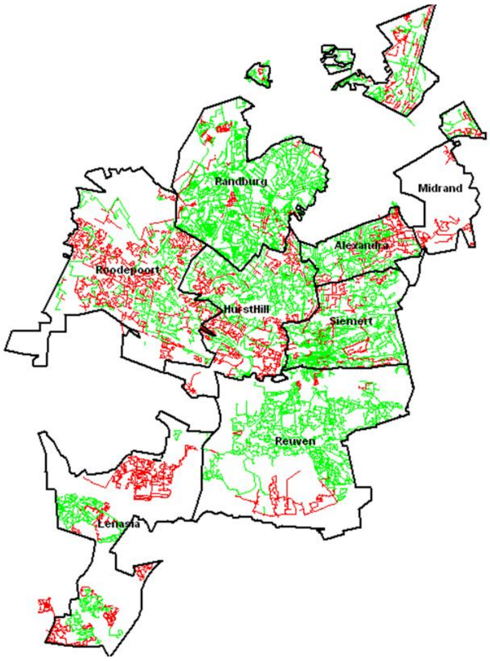

Figure 7: Criticality map, indicating in red all feeders where the actual SAIDI is much worse than the expected SAIDI

4.3 Impact of different performance improvement interventions

City Power has identified specific performance improvement interventions to improve the performance of their networks. The simplified approach was used to model the expected performance improvement that each intervention could potentially have. Each intervention is discussed briefly below:

Change the dispatch time:

City Power is currently experiencing a longer dispatch time than can be reasonably expected. . It is estimated that this dispatch duration can be reduced by almost 90%. The scenario modelled used a dispatch time of 12.5% of the current estimated dispatch time.

Build test branch capacity:

Long outage durations are currently being experienced with cable faults, due to limited capacity in the cable test branch department. If additional capacity is built in this department, it is surmised that the cable repair durations can reduce by up to 50%.

Improve the customer restoration factor (CR factor):

The City Power networks have a high level of interconnectivity. A large percentage of the customer base interrupted by an outage can therefore be supplied via an interconnector while the network fault is being repaired. However, operators do not always make use of these interconnectors due to the additional effort required with the switching of the networks. A scenario was modelled where the customer restoration factor is increased from 80% to 95% as a result of the effective application of interconnections.

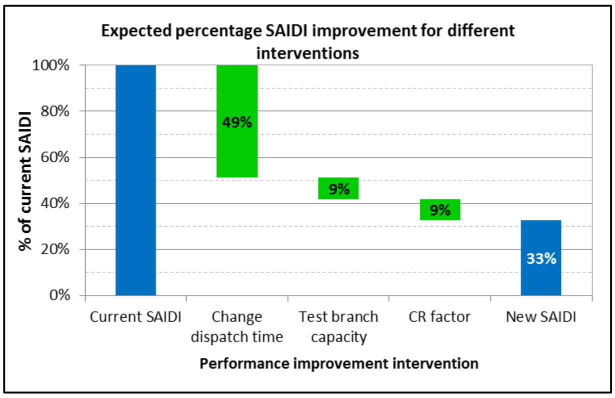

Figure 8: Expected percentage SAIDI improvement achieved with different interventions

The modelled outcomes of these interventions are shown in Figure 8. This figure shows that the identified interventions can reduce the expected City Power SAIDI by 67% if all other parameters are kept constant. City Power network performance engineers can use these results to make an informed decision on where to invest, in order to improve network performance going forward.

5 Summary and conclusion

The value of this simplified modelling approach can be explained as follows:

a) By understanding the realistically expected, designed level of performance, resources can be correctly focused and applied to make a difference where the most return on effort and investment would be achieved.

b) Although a high level of accuracy is obtained using PowerFactory, this simplified modelling approach enabled City Power to determine the expected "as-designed" performance of all their networks in less than four months and with a relatively low financial investment.

c) In cases where the expected designed performance is inherently much worse than City Power's stakeholders' expectations, informed decisions can be made regarding potential design changes and capital and refurbishment investment requirements to move such infrastructure performance levels to expected levels.

d) By modelling the networks, the network performance engineers develop a better understanding of what performance levers and geographical areas require additional focus to achieve the best overall system-level network performance.

e) The approach highlights potential deficiencies in network information and data. This data is crucial for proper management of the networks and can help guide efforts to improve specific elements, which in turn will also assist with improved overall decision-making and day-to-day operational management.

f) By using this modelled approach, it is possible to develop cost- and time-effective "what if" scenarios that can support better-informed strategic, executive and tactical decision-making about network performance, investment decisions and future potential network developments.

g) The approach developed is generic in nature and can be applied in any electrical distribution utility, with a relatively small investment in terms of resources and with minimal detailed technical information.

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