AN ANALYTICAL FRAMEWORK TO UNDERSTAND AND MANAGE RELIABILITY IN ELECTRICITY DISTRIBUTION NETWORKS

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ABSTRACT

We propose a framework to understand and manage reliability in distribution networks, based on the analytical breakdown of popular indexes, such as SAIDI and TIEPI. Our aim is to isolate and quantify the key determinants of reliability, providing a tool that decision-makers can use to understand the past and make decisions for the future.

The framework may be used to support the definition of reliability improvement strategies (e.g. feeder refurbishment vs. investment in automation vs. additional outage handling crews vs. new maintenance rules) and enables a systematic evaluation of the merit of past decisions. Additionally, it may be used to quantify the individual contribution of different functional areas (e.g. planning, operation, maintenance) to overall network reliability, much like we quantify the individual impact of each area in CAPEX and OPEX expenditure. This knowledge can support budgeting decisions and even be incorporated in scorecards, to provide targeted incentives to reliability.

In a context where performance-based regulation is gaining importance, this framework may also be useful for regulators, supporting the design of incentive schemes and the evaluation of investment proposals. Above all, the framework can help institutions, departments and individuals with very different perspectives to develop a shared understanding of how their decisions interact and contribute to the overall reliability of a network.

INTRODUCTION

Network reliability, as measured by popular indexes such as SAIFI, SAIDI or TIEPI, reflects the combined impact of very different drivers, such as equipment failure rates, network topology, effectiveness of outage handling processes, performance of protection schemes and environmental factors. As such, to manage reliability efficiently, we need a quantitative understanding of the way those drivers influence it – e.g. it is not enough to know how a given factor affects reliability, we also need to know by how much.

Distribution networks are very diverse in terms of materials, design, age, topology, protection schemes, operation practices, etc. Because of this diversity, we usually have to perform individual network simulation studies whenever we need to estimate the potential of specific projects to improve reliability. While this approach is indispensable to refine decisions and fine tune projects, it doesn't produce the type of general insights which may be used to define broad strategies and guidelines for investment portfolio management.

On the opposite extreme, traditional reliability improvement approaches based on ranking the worst performing feeders, as measured by aggregate indexes, are not efficient because they ignore the underlying causes of that performance and, therefore, often miss the best improvement opportunities.

Applied to specific cases, the framework proposed in this paper enables a quantitative understanding of the factors that have driven past reliability results. As such, it provides a good starting point to design a targeted strategy to improve future reliability by acting on the correct drivers. Because the framework relies simply on a rigorous analytical breakdown of indexes and the use of past reliability data, it is firmly anchored in reality and imposes a systematic check of the merit of past decisions.

ANALITICAL TREATMENT OF INDEXES

In this paragraph we derive analytical expressions that help us understand exactly how individual outages influence global reliability scores. We'll focus on the performance of distribution feeders to avoid an excessively abstract discussion. However, most concepts and tools can be generalized to other asset types.

SAIDI

The acronym SAIDI stands for *system average interruption duration index*. This reliability index is defined as the sum of the interruption time experienced by each customer, divided by the total amount of customers.

From the perspective of the utility it is more useful to regard SAIDI as the result of a series of outages (which have causes, failure modes, etc.), instead of individual customer interruptions. To focus on this perspective, we depict the number of customers interrupted over the duration of an outage, as shown in Figure 1 bellow.

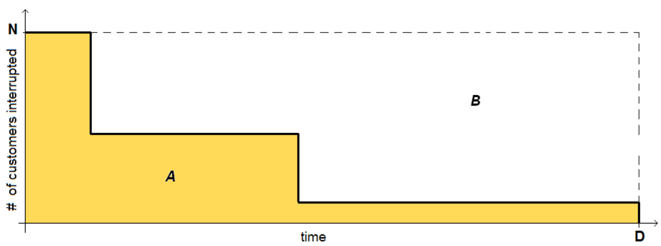

Figure 1 – Graphical representation of the incremental contribution of an outage to SAIDI (given by area *A*)

The generic outage represented in Figure 1 starts with an initial interruption, for example due to a fault in a feeder. As a result, the *N* customers served by the feeder experience an interruption. Following the beginning of the outage, maneuvers may be conducted to isolate the fault and restore power to an increasing[1] amount of customers. The outage ends when power is restored to the last customer, after an amount of time *D* – the outage duration. Referring to Figure 1, the **incremental contribution of this generic outage to SAIDI** is given by area *A* – that is, the integral over time of the number of customers interrupted. In the graph, the rectangle of area *A+B*, or equivalently the area given by *N*x*D*, represents the maximum potential contribution of the outage to SAIDI, which would happen if no restoration maneuvers were conducted. So, area *B* represents the incremental SAIDI avoided by the execution of partial restoration maneuvers. Using these concepts and notation, we define for each outage a quantity called ***ineffectiveness of restoration maneuvers*** – we'll use de symbol ε – as the ratio given by:

$$\varepsilon = \frac{A}{A+B} = \frac{\int_{t=0}^{D} n(t)dt}{N \times D} \quad (1)$$

where *n(t)* represents the number of customers interrupted at each instant *t*, implying *N=n(0)*, *A* and *B* correspond to the areas identified in Figure 1 and *D* is the duration of the outage. With this definition, ε represents the SAIDI increment caused by a given outage as a fraction of the maximum potential increment. This parameter is equal to one if no partial restoration maneuvers are done and tends to zero as the effectiveness of restoration maneuvers increases.

Building on these concepts, we can express SAIDI as the result of a series of outages, as follows:

$$SAIDI = \frac{\sum_{i=1}^{O} (N_i \cdot D_i \cdot \varepsilon_i)}{N_{total}} \quad (2)$$

with:

O - total number of outages that occurred over a given time period (usually one year) in a certain feeder, or set of feeders (in a substation, a region, a country, etc.);

N_{total} - total number of customers relevant for SAIDI computation (those served by the relevant feeder, substation, region, country, etc.);

N_i - number of customers interrupted at the beginning of outage *i*;

D_i - duration of outage *i*, from the beginning until the last customer is reconnected;

ε_i - *ineffectiveness of restoration maneuvers* of outage *i*, as defined in equation (1).

Simple manipulation of equation (2) yields:

$$SAIDI = \frac{O}{N_{total}} \cdot \frac{\sum_{i=1}^{O} (N_i \cdot D_i \cdot \varepsilon_i)}{O} \quad (3)$$

In equation (3) the fraction on the right corresponds, by definition, to the expected value of the quantity in parenthesis, that is, the expected value of the incremental contribution of an outage to SAIDI. So, we can write:

$$SAIDI = \frac{O}{N_{total}} \cdot \overline{N \cdot D \cdot \varepsilon} \quad (4)$$

where $\overline{N \cdot D \cdot \varepsilon}$ symbolizes the expected value of the product of the quantities *N*, *D* and ε, that characterize each outage, taken over the set of all relevant outages (the set of *O* outages).

The expected value of the product of two random variables can be expressed as:

$$\overline{x \cdot y} = \overline{x} \cdot \overline{y} + Cov(x, y) \quad (5)$$

where *Cov(x,y)* denotes the covariance of random variables *x* and *y*. Using this formula we can substitute in equation (4) to obtain:

$$SAIDI = \frac{O}{N_{total}} \cdot \left[\overline{N} \cdot \overline{D \cdot \varepsilon} + Cov(N, D \cdot \varepsilon)\right] \quad (6)$$

With another substitution step and some additional manipulation we get equation (7).

$$SAIDI = \frac{1}{N_{total}} \cdot O \cdot \overline{N} \cdot \overline{D} \cdot \overline{\varepsilon} \cdot \left(1 + \frac{Cov(D, \varepsilon)}{\overline{D} \cdot \overline{\varepsilon}} + \frac{Cov(N, D \cdot \varepsilon)}{\overline{N} \cdot \overline{D} \cdot \overline{\varepsilon}}\right) \quad (7)$$

Where:

D - duration of the outages (as illustrated in Figure 1);

N - number of customers affected at the initial instant of outages (as illustrated in Figure 1);

ε - *ineffectiveness of partial restorations*, as defined in equation (1);

$\text{cov}(x, y)$ - covariance of variables *x* and *y*, for the set of *O* outages;

$\overline{X}$ - average of variable *X*, taken over the set of *O* outages.

Equation (7) provides the analytical framework we need to understand what drives SAIDI and what the most efficient ways of reducing it are. For any given feeder, or arbitrary group of feeders, the equation shows how SAIDI depends on:

- the number of customers served by the feeder or group of feeders;
- the number of outages that occur in the relevant period of time;
- the average number of customers interrupted at the beginning of outages;
- the average duration of outages;

1 There is no requirement for the number of customers interrupted to decrease over time; it may increase as well, even above N, although this is uncommon and, naturally, something utilities try to avoid.

- the average *ineffectiveness of restoration maneuvers*;
- a factor, in parenthesis, that is determined by some statistical properties of the outages.

Focusing on the factor in parenthesis, we can see that the second parcel is a normalized measure of the covariance of the duration of outages with the *ineffectiveness of restoration maneuvers*. This parcel is negative if the effectiveness[2] of partial restoration maneuvers is higher for long outages than for short ones, it is null if there is no correlation and it is positive otherwise. So, SAIDI will be lower, the lower this covariance, which is simply a way to say that, everything else being equal, SAIDI will be lower if a utility is particularly effective at minimizing the impact of long outages through partial restoration maneuvers.

The third parcel inside the parenthesis in equation (7) measures whether those outages that affect large numbers of customers are also the longest and/or those where restoration maneuvers are not very efficient. Naturally, everything else being equal, SAIDI will be higher in those circumstances. Conversely, SAIDI will be lower if a utility is particularly apt at shortening or minimizing the impact of those outages that affect large numbers of customers.

Breaking the number of outages into failure rate and quantity of assets is useful in order to compare the relative performance of different quantities of assets, like feeders with different lengths. In the case of distribution feeders, failure rates are often expressed per unit of length[3], so, defining the failure rate as $\alpha = O/L$ and substituting in equation (7), we get:

$$SAIDI = \frac{1}{N_{total}} \cdot L \cdot \alpha \cdot \overline{N} \cdot \overline{D} \cdot \overline{\varepsilon} \cdot \left(1 + \frac{Cov(D,\varepsilon)}{\overline{D} \cdot \overline{\varepsilon}} + \frac{Cov(N, D \cdot \varepsilon)}{\overline{N} \cdot \overline{D} \cdot \overline{\varepsilon}} \right) \tag{8}$$

where L is the total length of the feeder, or group of feeders, and α is the corresponding failure rate.

In summary, equation (8) shows that SAIDI is proportional to the **quantity of assets** (in this case the length of a feeder or group of feeders), their **failure rate**, the **average duration of outages**, the **average number of customers affected in outages** and the **average (in)effectiveness of restoration maneuvers**. Additionally, it shows that SAIDI also depends on two covariance parameters that essentially measure the tendency of negative factors – long duration, many customers interrupted and ineffective restoration maneuvers – to occur simultaneously, resulting in high impact outages.

TIEPI

Some countries, like Portugal and Spain, use a reliability index with the acronym TIEPI, which focuses on the amount of power interrupted, instead of the number of customers interrupted. TIEPI can be defined as:

$$TIEPI = \frac{1}{P_{base}} \cdot \sum_{i=1}^{O} \int_{t=0}^{D_i} p_i(t) \cdot dt \tag{9}$$

with:

$p_i(t)$ - sum of the power installed in all customers interrupted at time t of outage i;

P_{base} - reference power base, corresponding to the total power installed in all customers[4] served by the feeder, or group of feeders, in question.

The treatment of this index is analogous of that of SAIDI, with the major difference being that number of customers is replaced by the power installed. So, for TIEPI we redefine the *ineffectiveness of restoration maneuvers* (ε) as follows:

$$\varepsilon = \frac{\int_{t=0}^{D} p(t)dt}{P \times D} \tag{10}$$

where $p(t)$ represents the number of customers interrupted at each instant t, implying $P=p(0)$ and D is the duration of the outage. With this definition, ε represents the TIEPI increment caused by a given outage as a fraction of the maximum potential TIEPI increment.

For TIEPI, equations (11) and (12), bellow, are analogous to equations (7) and (8) for SAIDI and are obtained in much the same way.

$$TIEPI = \frac{1}{P_{base}} \cdot O \cdot \overline{P} \cdot \overline{D} \cdot \overline{\varepsilon} \cdot \left(1 + \frac{Cov(D,\varepsilon)}{\overline{D} \cdot \overline{\varepsilon}} + \frac{Cov(P, D \cdot \varepsilon)}{\overline{P} \cdot \overline{D} \cdot \overline{\varepsilon}} \right) \tag{11}$$

$$TIEPI = \frac{1}{P_{base}} \cdot L \cdot \alpha \cdot \overline{P} \cdot \overline{D} \cdot \overline{\varepsilon} \cdot \left(1 + \frac{Cov(D,\varepsilon)}{\overline{D} \cdot \overline{\varepsilon}} + \frac{Cov(P, D \cdot \varepsilon)}{\overline{P} \cdot \overline{D} \cdot \overline{\varepsilon}} \right) \tag{12}$$

with:

P_{base} - total number of customers relevant for SAIDI computation (for example, those connected to feeder);

P - total power interrupted at the initial instant of outages;

ε - *ineffectiveness of partial restorations*, as defined in equation (10);

Equation (12) shows that TIEPI is proportional to the **quantity of assets** (for example, the length of a feeder or group of feeders), their **failure rate**, the **average**

2 We use the *ineffectiveness* of partial restoration maneuvers (ε) for analytical manipulation because it results in more compact equations, but we often discuss *effectiveness* because it a more natural concept. In any case, given our definition of ε, the effectiveness of maneuvers is simply the complement to one of the ineffectiveness; that is: $(1-\varepsilon)$.

3 Naturally, different units may be appropriate for other asset types (e.g. failures per transformer). Even for feeders, we could conceivably find that other failure drivers are more appropriate than length (e.g. the number of poles in an overhead line).

4 Usually the index is defined with a reference power base corresponding to the power installed in MV/LV transformers (those of MV customers and those in distribution substations).

duration of outages, the **average power interrupted** and the **average (in)effectiveness of restoration maneuvers**. Additionally, it shows that TIEPI also depends on two covariance parameters that essentially measure the tendency of negative factors – long duration, large amounts of power and ineffective restoration maneuvers – to occur simultaneously, resulting in high impact outages.

SAIFI

Compared to SAIDI, SAIFI is a simpler measure of reliability, in the sense that it captures less information. In computing SAIFI, all customer interruptions are treated equally, regardless of their duration.

The index is defined as the number of customer interruptions divided by the number of customers, but from the perspective of outages, we can express it as:

$$SAIFI = \frac{\sum_{i=1}^{O} N_i}{N_{total}} \tag{13}$$

where O is the number of outages and N_i represents the number of customers interrupted[5] in outage i.

From equation (13) we can see that the incremental contribution of an outage to SAIFI is simply proportional to the number of customers interrupted. For SAIFI, the analogous of equations (8) and (12) is simply:

$$SAIDI = \frac{1}{N_{total}} \cdot L \cdot \alpha \cdot \overline{N} \tag{14}$$

where $\overline{N}$ represents the average number of customers interrupted in outages, L the total length of the feeder set of feeders under consideration and α their failure rate.

It is clear from equation (14) that, by comparison with SAIDI and TIEPI, SAIFI depends on fewer factors and reflects essentially the reliability of assets (failure rates) and the quantity of customers and assets per feeder.

USING THE FRAMEWORK

In this paragraph we discuss how to apply the tools just developed to the type of data that utilities generally collect. We focus on SAIDI, but the concepts and conclusions are readily transposable to the other indexes.

To begin the analysis of past performance we need a database (which most utilities keep) with: feeders, feeder lengths, outages, causes, failure modes and individual customer interruptions. Additionally, for **each outage**, we compute and record: the **number of customers interrupted at the beginning of the outage** and the **ineffectiveness of partial restoration maneuvers**, as defined in equation (1). With this information we are able to compute every parameter of equation (8), for an arbitrary group of outages. In particular, we can group outages by feeder or set of feeders (regions, technologies, age, etc.) and, crucially, by **outage cause** and **failure mode**. The best way to group outages depends on what we want to investigate and generally an exploration of the data from different perspectives is in order.

With outages organized in appropriate sets, we can compute and analyze the parameters of equation (8). Analyzing and comparing these parameters for different feeders, feeder groups, outage causes and failure modes provides a deep understanding of the drivers of past reliability results; an understanding that is impossible to attain simply by analyzing aggregate SAIDI results.

Next we leave very brief and simple example of analysis, based on the synthetic data of Table 1.

Feeder / feeder groups	*SAIDI*	N_{total}	*L*	α	*N*	*D*	ε	*(...)*
	min.	*cust.*	*km*	*out./km*	*cust.*	*min.*	*%*	*-*
Feeder A1	33,8	2500	35	0,060	2500	65	25%	0,99
Feeder A2	33,7	4500	15	0,060	4500	90	40%	1,04
Feeder A3	33,5	3000	30	0,120	3000	40	25%	0,93
Region A	33,6	10000	80	0,083	3045	55	27%	1,13
Region B	33,4	50000	530	0,050	3500	58	28%	1,11

Table 1 – Illustrative data showing SAIDI and its components. The symbol *(...)* represents the quantity in parenthesis in equation (8).

We can see that while all feeders and feeder groups in Table 1 have approximately equal SAIDI values, this hides important differences, revealed only by the analysis of its components.

In the case of feeder A2, its short physical length hides the fact that many customers are connected to it (to the same circuit breaker), that outages are taking a long time to resolve and that there is reduced capacity to restore power with maneuvers. At first sight, it seems a good candidate to have reclosers or other automation installed.

In the case Feeder A3, a quick outage resolution time is masking a high failure rate. The best improvement option probably involves maintenance and/or refurbishment.

The exact same principles apply to the analysis of groups of feeders. The higher failure rate of region A is camouflaged by small differences in the remaining parameters. An analysis of the data by outage cause and failure mode should reveal many other details.

Beyond understanding past performance, we can use the framework to estimate the future. The idea is simply to estimate the impact of potential strategies or projects on the different components of SAIDI and from there compute the expected impact on the aggregate index.

Finally, in terms of further research, it would be desirable to apply the framework to large quantities of outage data and investigate the results for different **outage causes** and **failure modes**. An analysis of the statistical properties of the different components of the indexes, involving long time series, should also be useful to develop predictive models based on this framework. In principle, studding individual components should be more revealing than studding aggregate indexes.

5 Generally, the number of customers interrupted in an outage coincides with the number of customers interrupted at the beginning of that outage, but this is not necessarily true for all outages. In this sense, we introduce here a slight redefinition of the symbol *N* for SAIFI treatment.