Reliability Indices

Tom Short
EPRI PEAC

1462 Erie Blvd, Schenectady, NY 12305
518-374-4699x14 t.short@ieee.org

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Introduction

Reliability of power delivery varies widely from customer to customer and from utility to utility. Almost all customers expect good power delivery. But, power outages disrupt more businesses than any other factor (see Figure 1). In this paper, we'll define the most-used distribution reliability indices and look at results from various surveys. Circuit arrangements, storms, exposure, protection practices, and circuit voltage—we'll investigate how each of these impacts reliability statistics. Finally, we'll look at improving reliability statistics—what is effective and how to rank projects.

Reliability statistics, based on long-duration interruptions, are the primary benchmark used by utilities and regulators to identify service quality. Faults on the distribution system cause most long-duration interruptions; a fuse, breaker, recloser, or sectionalizer locks out the faulted section.

Many utilities use reliability indices to track the performance of the utility or region or circuit. Regulators require most investor-owned utilities to report their reliability indices. The regulatory trend is moving to performance-based rates where performance is penalized or rewarded based on sustained interruptions as quantified by reliability indices. Some utilities also pay bonuses to managers or others based in part on indices. Some commercial and industrial customers ask utilities for their reliability indices before locating a facility within the utility's service territory.

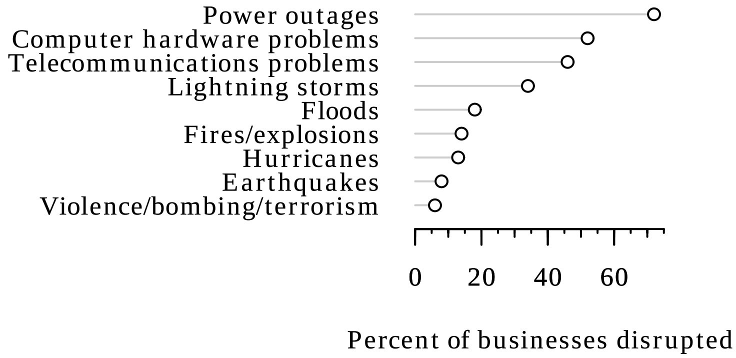

Figure 1. Percent of US businesses disrupted by the given problem. [Rodentis, 1999]

Reliability Indices

Utilities most commonly use two indices, SAIFI and SAIDI, to benchmark reliability. These characterize the frequency and duration as follows:

SAIFI, System average interruption frequency index

$$\text{SAIFI} = \frac{\text{Total number of customer interruptions}}{\text{Total number of customers served}}$$

Typically, a utility's customers average between one and two sustained interruptions per year.

SAIDI, System average interruption duration frequency index

$$\text{SAIDI} = \frac{\text{Sum of all customer interruption durations}}{\text{Total number of customers served}}$$

SAIDI measures the total duration of interruptions. SAIDI is cited in units of hours or minutes per year. Other common names for SAIDI are CMI and CMO abbreviations for customer minutes of interruption or outage.

SAIFI and SAIDI are the most-used pair out of many reliability indices, which look like a wash of acronyms—most importantly, *D* stands for duration and *F* stands for frequency. Another related index is CAIDI, the average repair time:

CAIDI, Customer average interruption duration frequency index

$$\text{CAIDI} = \frac{\text{SAIDI}}{\text{SAIFI}} = \frac{\text{Sum of all customer interruption durations}}{\text{Total number of customer interruptions}}$$

Survey results for SAIFI and SAIDI are shown in Table 1. Most of the data is for a cross section of North American utilities. Figure 2 shows the distribution of utility indices from a Canadian Electricity Association survey.

Table 1. Reliability indices found by major industry surveys.

	SAIFI, number of interruptions per year			SAIDI, hours of interruption per year		
	25%	50%	75%	25%	50%	75%
[IEEE Std. 1366-1998]	0.90	1.10	1.45	0.89	1.50	2.30
[EEI, 1999] (excludes storms)	0.92	1.32	1.71	1.16	1.74	2.23
[EEI, 1999] (with storms)	1.11	1.33	2.15	1.36	3.00	4.38
[CEA, 2001] (with storms)	1.03	1.95	3.16	0.73	2.26	3.28
[PA Consulting, 2001] (with storms)				1.55	3.05	8.35
Large City Survey [IP&L, 2000]	0.72	0.95	1.15	1.02	1.64	2.41

A B C represent the lower quartile A, the median B, and the upper quartile C of utility indices.

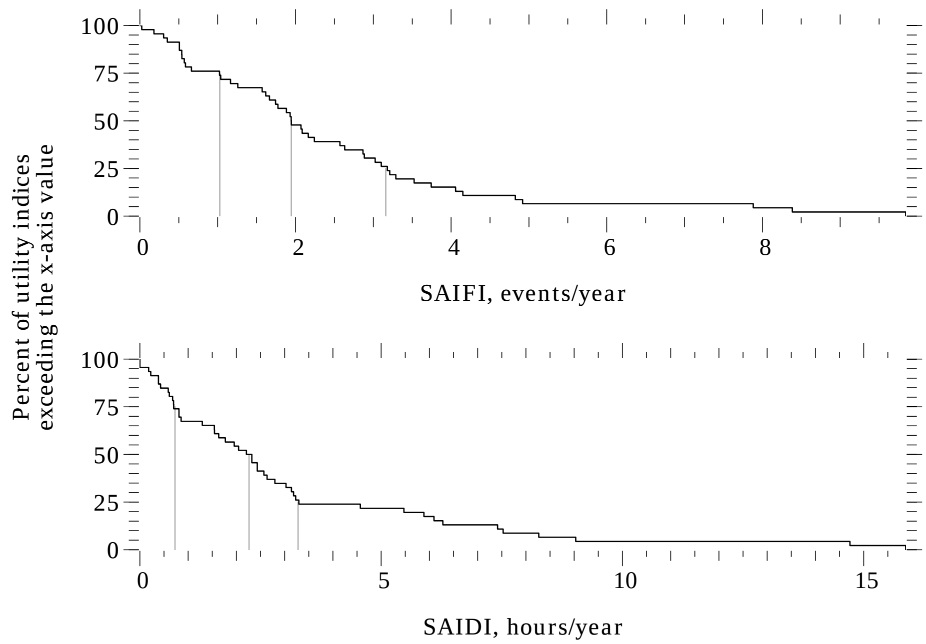

Figure 2. Distribution of utility indices in Canada (CEA survey, 36 utilities, two-year average). [CEA, 2001]

Also used in many other industries, the availability is quantified as:

ASAI, Average service availability index

$$\text{ASAI} = \frac{\text{SAIDI}}{\text{SAIFI}} = \frac{\text{Customer hours service availability}}{\text{Customer hours service demanded}}$$

We can find ASIFI from SAIDI specified in hours as:

$$\text{ASAI} = \frac{8760 - \text{SAIDI}}{8760}$$ (Use 8784 hours per year for a leap year.)

By and large, utility availability is good; a SAIDI of two hours is a 99.977% availability.

Within a utility or operating area, customers have a wide range of reliability because of differences in circuit exposure, voltage, construction, and age. Figure 3 has two examples of weighted distributions that show the spread of customer reliability. Customer reliability is not normally distributed. A skewed distribution such as the log-normal distribution is more appropriate and has been used in several reliability applications [Brown and Burke, 2000; Christie, 2001]. A log-normal distribution is appropriate for data that is bounded on one side by zero. The skewed distribution has several ramifications:

- The average is higher than the median. The median is a better representation of the "typical" customer.
- Since the indices are all averages, poor performing customers and circuits dominate the indices.
- Storms and other outliers easily skewed the indices.

Realize that SAIFI and SAIDI are weighted performance indices. They stress the performance of the worst-performing circuits and the performance during storms. SAIFI and SAIDI are not necessarily good indicators of the typical performance that customers have. And, they ignore many short-duration events such as voltage sags that disrupt many customers.

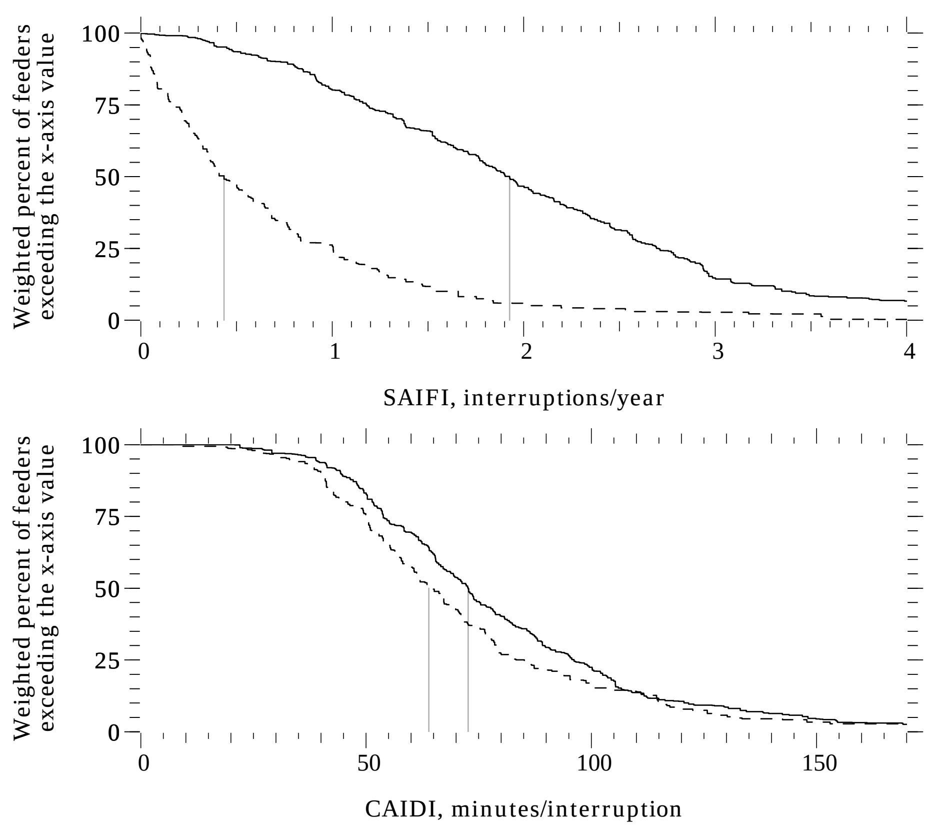

Figure 3. Reliability indices by feeder for two utilities. Forced events only—storm, scheduled, substation, and transmission events are excluded. The total SAIFI including all events was 0.79 for the first utility and 3.4 for the second.

Major Events (Storms)

Much of the reliability data reported to regulators excludes storm or major event interruptions. Major storms significantly alter the reliability indices. So many regulators allow exclusions based on the reasoning that a utility's performance during storms does not represent the true "everyday" performance of the utility's distribution system.

Storms are defined differently by different utilities and regulators; some use a percentage of customers interrupted in some way, and others use some form of weather-based classification. If storms are not excluded, reliability numbers go up as shown in Figure 4. The repair time (CAIDI) and the average total interruption time (SAIDI) increase the most if storm data is included. SAIFI is only moderately impacted.

During severe storms, crews from other service territories or other companies along with general mayhem add large roadblocks preventing utilities from keeping records needing for tracking indices. Expedience rules—should I get the lights back on or do paperwork?

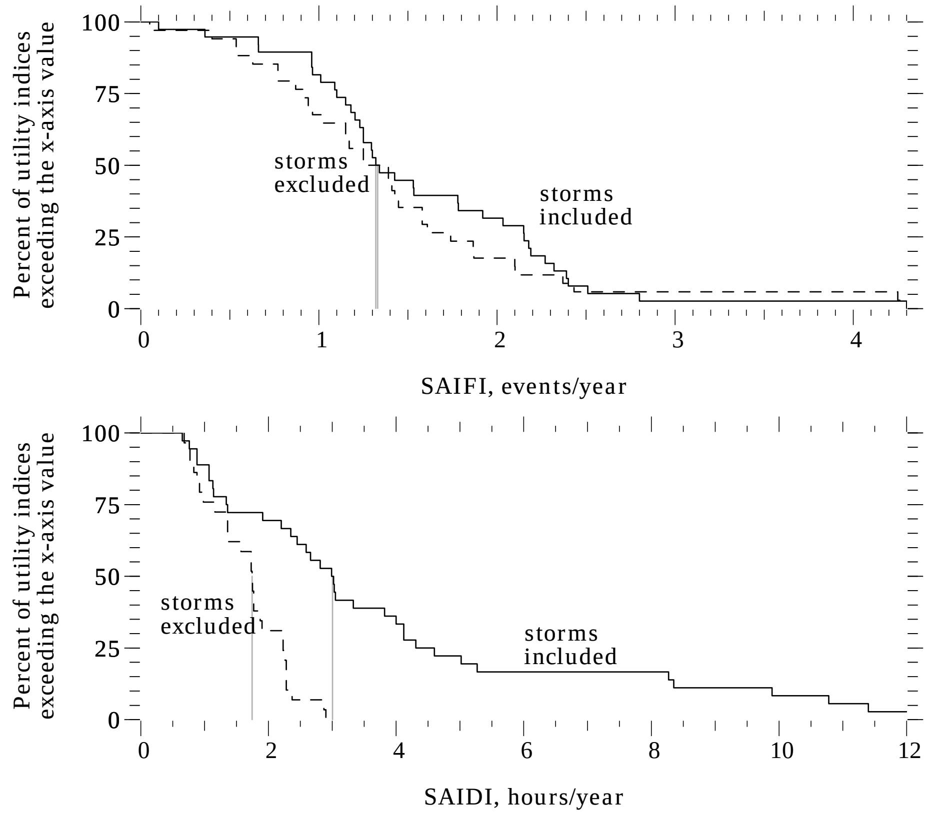

Figure 4. Distribution of utility indices with and without excluding storms. [EEI, 1999]

Various methods are used to classify storms. The two common categories are based on:

1. *Statistics*—A common definition is 10% of customers affected within an operating area.
2. *Weather*—Common definitions are “interruptions caused by storms named by the national weather service” and “interruptions caused during storms that lead to a declaration of a state of emergency.”

Some utilities exclude other interruptions including those scheduled or those from other parts of the utility system (normally substation or transmission caused interruptions). Both are done for the same reasons as storm exclusions: neither scheduled interruptions nor transmission-caused interruptions reflect the normal operating performance of the distribution system.

The IEEE working group appears to favor a statistical approach to classifying major events. An argument against this is that major substation or transmission outages can be “major events” and get excluded from indices. From the customer point of view, major event or no major event, an interruption is still a loss of production or spoiled inventory or a loss of productivity or a missed football game. For this reason, some regulators hesitate to allow exclusions.

Variables Affecting Reliability Indices

Circuit Exposure and Load Density

Longer circuits cause more interruptions. This is difficult to avoid on normal radial circuits, even though we can somewhat compensate by adding reclosers, fuses, extra switching points, or automation. Most of the change is in SAIFI; the repair time (CAIDI) is less dependent on circuit lengths. Figure 5 shows the effect on SAIFI at one utility in the southwest.

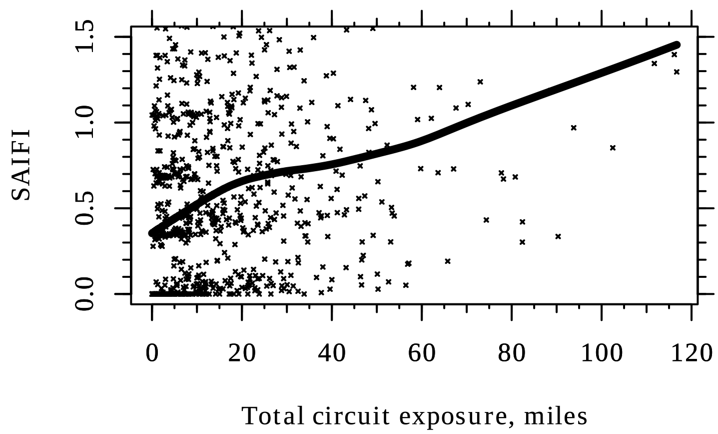

Figure 5. Effect of circuit length on SAIFI at the feeder level for one utility in the southwest US.

It is easier to provide higher reliability in urban areas: circuit lengths are shorter; more reliable distribution systems (such as a grid network) are more economical. The Indianapolis Power and Light survey results in Table 1 only included performance of utilities in large cities. As expected, the urban results were better than the other utility surveys shown on the list. Another comparison is shown in Figure 6—in all states, utilities with higher load densities tend to have better SAIFI's.

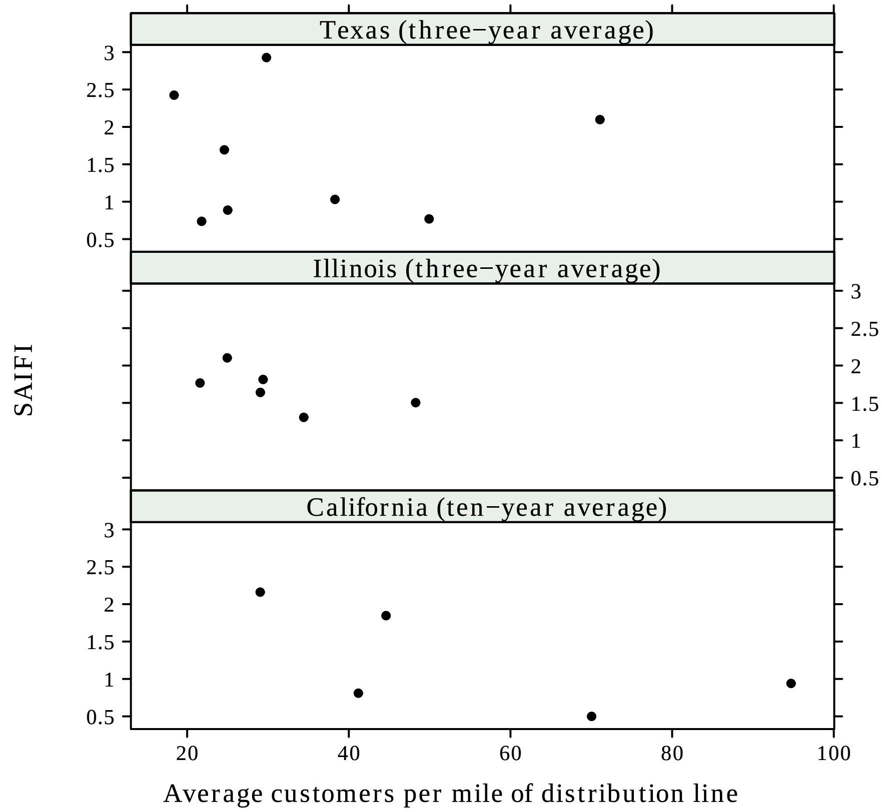

Figure 6. Effect of customer density on SAIFI.

Supply Configuration

The distribution supply greatly impacts reliability. Long radial circuits provide the poorest service; grid networks provide exceptionally reliable service. Table 2 gives estimates of the reliability of several common distribution supply types developed by New York City's Consolidated Edison. Note that the repair time (CAIDI) increases for the more urban configurations. Being underground and dealing with traffic increases the time for repairs.

Table 2. Comparison of the Reliability of Different Distribution Configurations [Settembrini et. al., 1991]

	SAIFI interruptions/year	CAIDI minutes/interruption	MAIFI momentary interruptions/year
Simple radial	0.3 to 1.3	90	5 to 10
Primary auto-loop	0.4 to 0.7	65	10 to 15
Underground residential	0.4 to 0.7	60	4 to 8
Primary selective	0.1 to 0.5	180	4 to 8
Secondary selective	0.1 to 0.5	180	2 to 4
Spot network	0.02 to 0.1	180	0 to 1
Grid network	0.005 to 0.02	135	0

Voltage

Higher primary voltages tend to be more unreliable, mainly higher-voltage circuits can have much longer lines. Figure 7 shows an example for one utility that is typical of many utilities—higher voltage circuits have more interruptions.

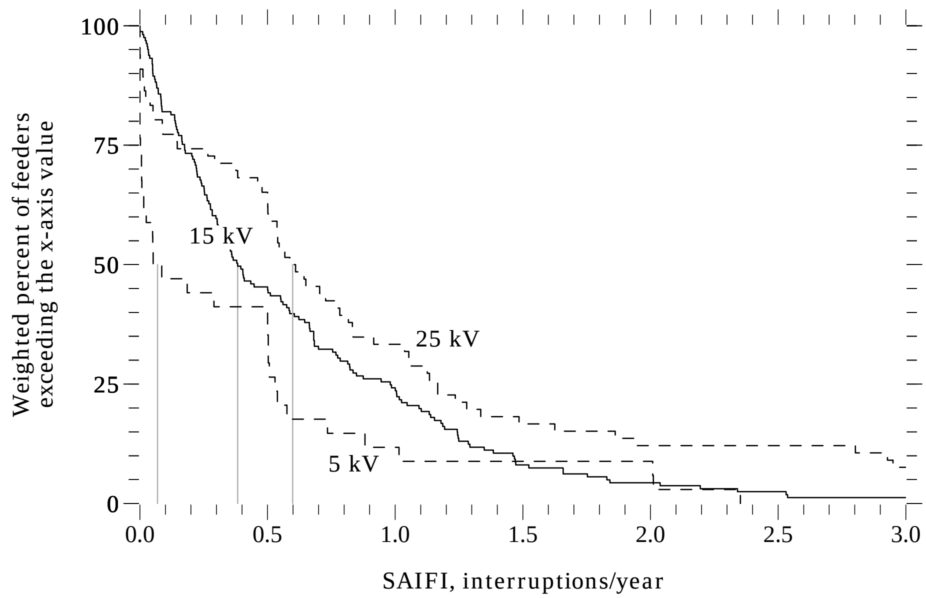

Figure 7. Effect of circuit voltage on feeder-level SAIFI for one utility in the southern US. Forced events only—storm, scheduled, substation, and transmission events are excluded.

General Ways to Improve Reliability

We have many different methods of reducing long-duration interruptions including:

- Reduce faults (tree trimming, tree wire, animal guards, arresters, circuit patrols, etc.).
- Find and repair faults faster (faulted circuit indicators, outage management system, crew staffing, etc.).
- Limit the number of customers interrupted (more fuses, reclosers, and sectionalizers)
- Only interrupt customers for permanent faults (reclosers instead of fuses, fuse saving schemes).

Whether we are trying to improve the reliability on one particular circuit or trying to raise the reliability system wide, the main steps are:

1. Identify possible projects.
2. Estimate the cost of each configuration or option.
3. Estimate the improvement in reliability with each option.
4. Rank the projects based on a cost-benefit ratio.

Prediction of costs is generally straightforward; predicting improvement is not. Some projects are difficult to attach a number to.

An important step in improving reliability is defining what measure to optimize: is it SAIFI, SAIDI, some combination, or something else entirely? The ranked projects change with the goal. Surveys have shown that frequency of interruptions is most important to customers (until you get to very long interruptions). Regulators tend to favor duration indicators since they are more of an indicator of utility responsiveness (and excessive cost cutting might first appear as a longer response time to interruptions).

Detailed analysis and ranking of projects can be done on a large scale. Brown et. al. [2001] provides an interesting example of applying reliability modeling to Commonwealth Edison's entire distribution system in Illinois to rank configuration improvements. Normally, large scale projects require simplification (and often a good bit of guesswork).

Identifying and Targeting Fault Causes

Tracking and targeting fault types helps identify where to focus improvements. If animals aren't causing faults, we don't need animal guards. Many utilities tag interruptions with identifying codes. The system-wide database of fault identifications is a treasure of information that we can use to help improve future reliability.

Different fault causes affect different reliability indices. Figure 8 shows the impact of several interruption causes on different reliability parameters for Canadian utilities. Impacts vary widely; for example, tree-caused faults had a high repair time but impacted fewer customers.

Tracking this type of data for a utility operating region helps identify the most common problems for that service area. These numbers change dramatically by region depending on weather, construction practices, load densities, and other factors.

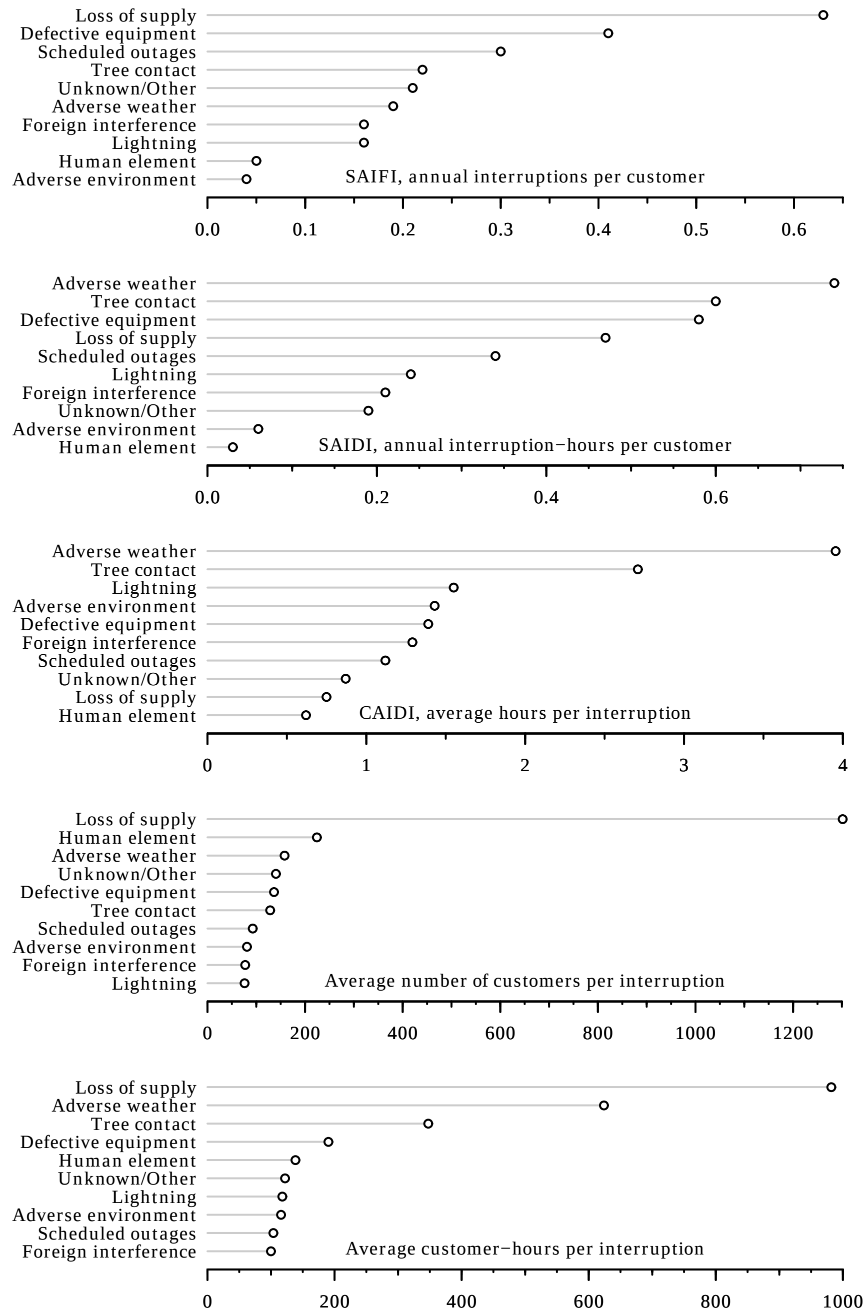

Figure 8. Root-cause contributors to different reliability parameters. [CEA, 2001]

Identifying and Targeting Circuits

Don’t treat all circuits the same. The most important sections are usually not the locations with the most faults per mile. The number of customers on a circuit and the type of customers on a circuit are important considerations. For example, a suburban circuit with many high-tech commercial customers should warrant different treatment than a rural circuit with fewer, mostly residential and agricultural customers (although the reliability indices are blind to this). How this is weighted depends on the utility’s philosophy.

Fault Reduction

An obvious approach to reliability improvement is to reduce the number of faults. In addition to long-duration interruptions, this strategy reduces the number of voltage sags and momentary interruptions and makes the system safer for workers and the public.

For many utilities, the best way to reduce faults is also an expensive and time consuming chore: tree trimming. It can also irritate communities. Here are some general recommendations for successful tree trimming:

- Remove trees whenever possible—this is the most effective fault-prevention strategy, and many land owners are willing to have trees removed.
- Target danger trees—trimming/removal is most effective if trees and branches that are likely to fail are removed or trimmed to safe distances. This does take some expertise by tree trimming crews.
- Target areas based on customer impact—as with any fault-reduction program, efforts are best spent on the poorest performing circuits that affect the most customers. Along the same thought, spend more on three-phase mains than on single-phase taps.

On underground circuits, many of the reliability problems can be tied to certain types and ages of cable, especially 1970's vintage HMWPE. Replacing those chronically bad sections is the most straightforward way of improving the fault rate on underground circuits. The most common replacement criteria is after two or three failures.

Adding reclosers, putting in more fusing points, automating switches—these configuration changes are predictable. Many computer programs will quantify these improvements.

Projects aimed at reducing the rates of faults—trimming more trees, adding more arresters, installing squirrel guards—are difficult to quantify. Improving fault-finding and repair are also more difficult to quantify. A sensitivity analysis helps when deciding on these projects. In the simplest form, rather than using one performance number, use a low, a best guess, and a high estimate. Pinpointing fault causes also helps frame how much benefit these targeted solutions can have (if there are few lightning-caused faults, additional arresters will provide little benefit).

On-site investigations of specific faults can help reduce subsequent faults. Faults tend to repeat at the same locations and follow patterns. For example, one particular type and brand of connector may have a high failure rate. If these are identified, replacement strategies can be implemented. Another example is animal faults—one particular pole, which happens to be a good travel path for squirrels, may have a transformer with no animal guards. The same location may have repeated outages. These may be difficult to find, but crews can be trained to spot pole structures where faults might be likely.

Overlooked Reliability Improvements

As a conclusion, we'll briefly look at two schemes for reliability improvement that are often overlooked:

- Use single-phase reclosers—Single-phase reclosers, in place of fuses, help improve reliability, especially on circuits with long taps. Using single-phase reclosers also helps on three-phase circuits—only one phase is interrupted for line-to-ground faults (which is most faults).
- Be careful when removing fuse saving—Utilities are moving to fuse blowing schemes (always let tap fuses blow) rather than fuse saving schemes (where a breaker or recloser tries to open before the fuse to clear temporary faults). This reduces the number of momentary interruptions but worsens reliability indices. To limit the impact on reliability indices, apply fuse blowing selectively based on the customer mix on the circuit. Monitor the transition closely to identify lateral fuses that are operating excessively.

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