A CUSTOMER-ORIENTED APPROACH TOWARDS RELIABILITY INDICES

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ABSTRACT

This paper introduces a reliability index that is directly linked to the satisfaction of individual customers with the experienced reliability of supply. The definition of the index is based on the observation that customers are satisfied as long as they have less than 3 interruptions per year, none of which lasts longer than 8 hours. The customer dissatisfaction index (CDI) is defined as the probability that this condition is fulfilled for a given customer. Mathematical expressions are obtained for the CDI; its relation with existing indices is studied; and the results of a case study in a medium-voltage distribution network are presented.

INTRODUCTION

Many performance indices have been introduced that quantify the reliability of a distribution network, with SAIFI, SAIDI and CAIDI being most commonly used. IEEE Std. 1366 gives definitions for most of the indices in use [1]. Disadvantages with most existing indices are that they consider system averages and that they do not directly quantify the way in which a customer experiences the reliability of supply.

In this paper a new index is proposed that corresponds more closely with the reliability as experienced by customers. After the introduction of the index, relations are derived between the value of the new index and the load-point indices interruption frequency and expected interruption duration. The relation with system indices is also discussed. The new index is next calculated for an existing medium-voltage distribution network and for a number of alternatives. Finally a number of possible applications of the index are discussed.

CUSTOMER DISSATISFACTION INDEX

Customer satisfaction and dissatisfaction

One of the important findings in a previous (unpublished) study was that there seems to be a rather sharp threshold value for the customer satisfaction regarding reliability of supply. Complaints started when a customer experienced more than three interruptions per year, or one interruption longer than 8 hours. A customer that experienced less than four interruptions in a give year, all of which are shorter than 8 hours, was very unlikely to complain. Based on this observation it was decided to define the envelope of "acceptable supply" for a customer as three or less interruptions per year, each shorter than 8 hours, as shown in Figure 1. The vertical axis gives the number of interruptions experienced by a customer during a given year; the horizontal axis gives the longest interruption experienced during that year.

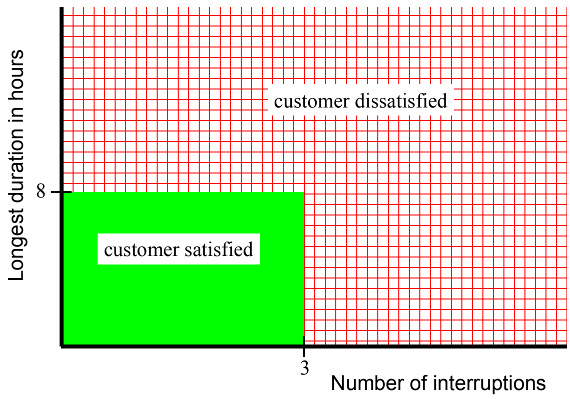

Figure 1 – Relation between number of interruptions, duration of interruptions and customer satisfaction.

Definition of CDI

The "*customer dissatisfaction index*" or CDI is defined as the probability that the supply for a given customer is of insufficient reliability. In this paper insufficient reliability is defined as at least one interruption longer than 8 hours or more than three interruptions of any duration longer than 3 minutes, during a given year (see Figure 1). Short interruptions, 3 minutes or less, are not covered in this study.

Note that the CDI is a load-point probability index (i.e. it holds for one location in the system) and that its value for a specific year cannot be measured. The index is a probability, whereas a measurement would give a value of one or zero for any year. When data over a long time period is available, an estimation of the probability can be obtained. But an accurate estimation would require many years of data.

The system average customer dissatisfaction index (SACDI) is the average value of the CDI over all customers:

$$\mathrm{SACDI} = \frac{1}{N}\sum_{i=1}^{N}\mathrm{CDI}_i \qquad (1)$$

This is a system index that can be obtained from measurements as the fraction of customers that experience Insufficient Security of supply during a given year. The expected value of this fraction equals the average of the CDI over all customers.

Expressions for CDI

During a given year, a customer experiences N interruptions, with durations T_1, T_2, T_3, etc. As defined in the previous section the CDI is the probability that a customer will experience too many (four or more) or too long (longer than 8 hours) interruptions. This probability is equal to one minus the probability that the customer will not experience such a situation.

$$CDI = 1 - \Pr\{nss\} \tag{1}$$

where "*nss*" stands for "no such situation", which can be split up in the following mutually-exclusive cases:

- No interruption.
- One interruption, shorter than 8 hours.
- Two interruptions, both shorter than 8 hours.
- Three interruptions, all three shorter than 8 hours.

Assume further that the first, second and third interruption have the same duration distribution and that they are stochastically independent with each other and with the number of interruptions. This gives the following expression for the probability:

$$\begin{aligned} CDI = 1 &- \Pr\{N=0\} \\ &- \Pr\{N=1\}\times\Pr\{T<8\} \\ &- \Pr\{N=2\}\times\left(\Pr\{T<8\}\right)^2 \\ &- \Pr\{N=3\}\times\left(\Pr\{T<8\}\right)^3 \end{aligned} \tag{2}$$

Assume further that the time between interruptions is exponentially distributed. This results in the following expression for the customer dissatisfaction index:

$$CDI = 1 - e^{-F} - Fe^{-F}P_8 - \tfrac{1}{2}F^2e^{-F}P_8^{\,2} - \tfrac{1}{6}F^3e^{-F}P_8^{\,3} \tag{3}$$

Where $P_8 = \Pr\{T<8\}$ is the probability that an interruption lasts less than 8 hours.

The above expression for the CDI has been calculated by assuming that the duration of an interruption follows a Weibull distribution. The probability distribution function of the Weibull distribution is:

$$F(t) = 1 - \exp\left(-\left(\frac{t}{\alpha}\right)^{\beta}\right) \tag{4}$$

with α the characteristic value and β the shape factor of the distribution. For $\beta = 1$ an exponential distribution is obtained with expected duration α. Note that the characteristic value α is, for non-exponential distributions, not equal to the expected value D of the duration. Instead they are related by a gamma function of the shape factor:

$$D = \alpha\Gamma\left(1+\frac{1}{\beta}\right) \tag{5}$$

From the probability distribution function, the required probability can be obtained as follows:

$$P_8 = 1 - \exp\left(-\left(\frac{8}{D}\Gamma\left(1+\tfrac{1}{\beta}\right)\right)^{\beta}\right) \tag{6}$$

The expressions derived above have been used to estimate the value of CDI for different values of interruption frequency and expected duration. The results are shown in Figure 2 and Figure 3 for Weibull distributions with a shape factor equal to 1.5 and 4, respectively. An exponential distribution has been assumed for the time between interruptions, in both cases.

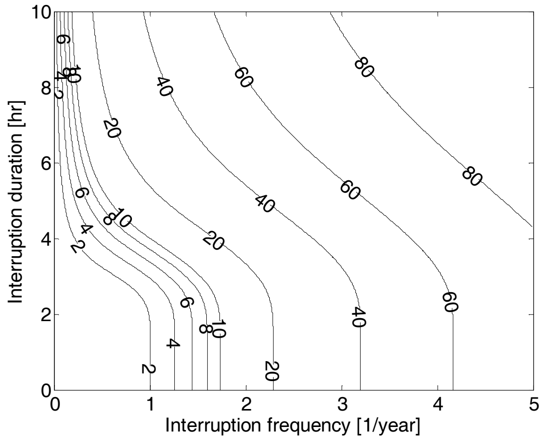

Figure 2 - Contour chart for CDI, with values in percent. Weibull distribution with shape factor 1.5.

For expected duration below a certain value (2 to 4 hours) the CDI value is only determined by the interruption frequency, as the probability that an interruption is longer than 8 hours is negligible. With increasing expected duration, the CDI value increases fast.

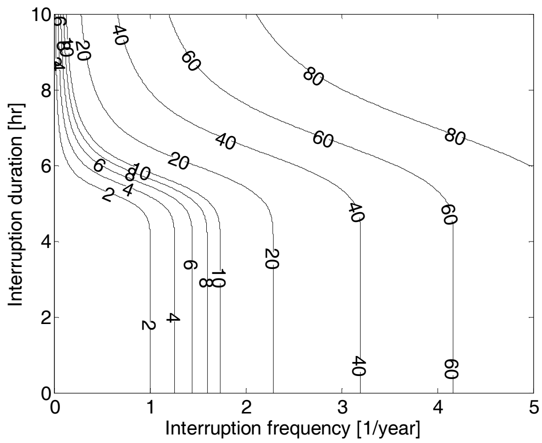

Figure 3 - Contour chart for CDI with values in percent. Weibull distribution with shape factor 4.

SACDI AND EXISTING INDICES

There is no direct relation between SACDI and existing system indices. The system-average customer dissatisfaction index is a separate index that may be used next to SAIFI, SAIDI and CAIDI.

The customer dissatisfaction index is a strongly non-linear function of the expected number of interruptions and the expected interruption duration at a load point. It further depends on the distribution of time between interruptions and duration of an interruption (*F* and *T*, respectively). The number of interruptions and, especially, the duration of interruptions vary strongly between different customers, so that average values of *F* and *T* do not give a good indication of the CDI for individual customers.

In some cases it is however desired to obtain an estimate of the SACDI for a feeder or a group of customers. The following approach may be taken in that case:

- Assume that all customers under consideration have the same expected number of interruptions and the same expected interruption duration. *F* and *T* can be calculated directly from SAIFI and CAIDI.
- Assume next that time between interruptions and duration of interruptions are exponentially distributed, or assume a shape factor for the Weibull distribution. The customer dissatisfaction index can be calculated from *F* and *T* under that assumption.
- As all customers have the same *F* and *T*, they also have the same CDI and this value is equal to the SACDI.

As a result the same expressions as before can be used, with *F*=SAIFI, *T*=CAIDI and SACDI=CDI.

The curves in Figure 2 and Figure 3 can be used to determine SAIFI and CAIDI requirements from SACDI requirements. For example an SACDI requirement of 0.2 can be achieved through SAIFI<2.2 int/yr and CAIDI<2 hr/yr, but also through SAIFI<0.9 int/yr and CAIDI<6 hr/yr. Here a shape factor equal to 1.5 (as in Figure 2) has been assumed. A different shape factor would give different results.

CASE STUDY

The customer dissatisfaction index as defined in this paper, has been calculated for the customers supplied from a rural medium-voltage distribution feeder. The feeder being studied is shown in Figure 4, where the small bars indicate disconnectors, the circles normally-open points and the arrows distribution transformers.

Reliability indices have been calculated for this network by using the power-system analys package NEPLAN [2]. Some additional calculations have been performed afterwards, starting from the NEPLAN results, to obtain the CDI for each load point. In the reliability calculations a distinction was made between long interruptions and very-long interruptions. The latter term refers in this context to interruptions lasting longer than 8 hours. These interruptions are of special interest as they directly contribute to the customer dissatisfaction index.

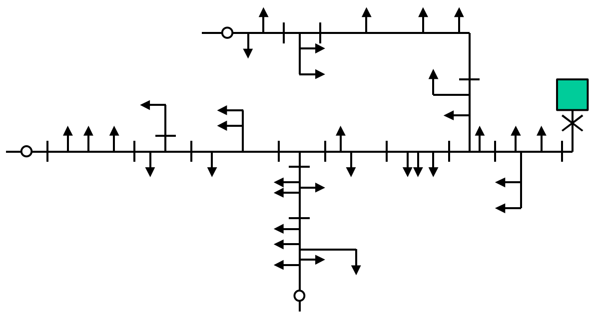

Figure 4 – Distribution network used in the case study.

The calculation results for the base-case are summarized in Table 1, where F_{vl} stands for the number of "very-long interruptions".

Table 1 – Reliability indices calculated for the base case.

	Whole network	Best customer	Worst customer
SAIFI	1.98 int/yr		
SAIDI	10.85 hr/yr		
CAIDI	5.47 hr/int		
F		1.98 int/yr	1.98 int/yr
Pr		10.40 hr/yr	11.39 hr/yr
F_{vl}	0.19 int/yr	0.10 int/yr	0.29 int/yr
CDI		0.21	0.32
SACDI	0.26		

To reduce the CDI for individual customers and the SACDI for the whole feeder a number of alternatives have been studied. The results are shown in Table 2 and Figure 5.

Table 2 – Reliability indices obtained by improvements in the distribution network.

	SAIFI (int/yr)	SAIDI (hr/yr)	SACDI
base case	1.98	10.85	0.26
underground cable	0.29	1.66	0.04
additional breakers	0.98	5.77	0.18
additional disconnectors	2.01	10.70	0.23
ring-main units	2.23	11.39	0.22

The system indices for the five cases are compared in Table 2. The installation of additional disconnectors and ring-main units gives an increase in SAIFI as the network contains more components, but a reduction of SACDI compared with the base case. A comparison for individual load points is shown in Figure 5. Again the use of underground cables gives the biggest improvement, but the, much cheaper, installation of a small number of additional disconnectors at strategic locations gives a huge improvement for the worstserved customers.

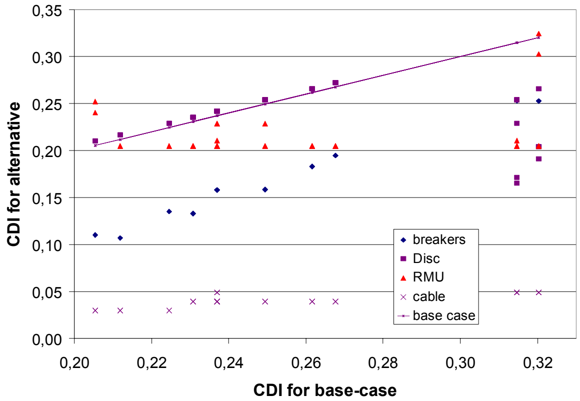

Figure 5 – comparison of the CDI between the base case (horizontal axis) and the other cases (vertical axis). The solid diagonal line corresponds to "no change in CDI".

APPLICATIONS OF CDI

Use of CDI in design

The index can be used in two different ways in a design criterion:

- The aim of the design is to limit the SACDI to a pre-defined threshold value.
- The aim of the design is to limit the number of customers for which the CDI exceeds a pre-defined threshold value.

An important question in the design process is: What is an acceptable level? This holds for CDI as well as for SACDI. This question requires further discussion. Gathering more information about existing values would be a feasible approach. With only the results from two networks as guidance, a CDI limit of 0.25 and a SACDI limit of 0.2 for each individual feeder, appear reasonable.

Of course also other considerations have to be made when deciding appropriate measures in the system, such as impact on system reliability parameters SAIFI, SAIDI and CAIDI, impact on maintenance, etcetera.

Use of CDI in performance reporting

The use of the customer dissatisfaction index in performance reporting is more straightforward. But an important observation that should be repeated here is that calculation of SACDI requires load-point CDI indices. System indices (even per feeder) cannot be used to calculate SACDI with sufficient accuracy.

It should also be noted that the observed value of CDI per customer is always one or zero; i.e. either the customer experiences more than three interruptions or at least one interruption longer than 8 hours or the customer does not experience this. The index to be reported is therefore the SACDI per feeder or for a group of feeders. Over a longer period (e.g. 10 years) an average yearly CDI can be reported for individual customers to be compared with calculated values.

It is recommended to calculate the SACDI per feeder for a number of selected feeders over a number of years using past data. This will provide some insight in the expected values.

Use of CDI in High-Level Network Planning

The use of CDI and SACDI in high level network planning allows estimating the cost due to insufficient reliability of supply. From SAIFI and CAIDI the SACDI can be roughly estimated by using the curves in Figure 2 and Figure 3. Knowing the SACDI the dissatisfaction cost can be estimated once the costs per customer are known. Where the cost per affected customer consists of:

- Cost for handling complaints
- Bad-will cost (e.g. lost energy customers)
- Cost for liabilities

CONCLUSIONS

A new reliability index has been defined that better corresponds to the reliability of supply as experienced by customers. The definition is based on the observation that customers are satisfied as long as they experience less than three interruptions per year, each lasting not longer than 8 hours. The same concept can be used for other limits on number and duration of interruptions, e.g. requirements set by the regulator in some countries.

The index has been successfully applied to an existing medium-voltage distribution network. It is shown that the index can be used as a design tool.

REFERENCES

[1] IEEE Std.1366-2003, *Guide for electric power distribution reliability indices*, May 2004.
[2] http://www.neplan.com

ACKNOWLEDGEMENTS

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