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What is reliability? Reliability and Reliability Indices in the Viewpoint of the Network Operator and in the Viewpoint of the Customer

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***Summary*: This paper explains the different definitions of the term „interruption" as used by the network operator and individual customers, especially industrial customers. The different viewpoints are strongly related to the different demands placed on these two stakeholders. Reliability indices are presented as a way to enable communication. A compatibility gap is identified due to the different demands on network operator and customer. Appropriate responsibility sharing is needed to remove this gap.**

Key words:
power-system reliability, interruptions, voltage dips, power quality, domestic customers, industrial customers, network operators

1 INTRODUCTION

A number of different definitions of the term „reliability" exist in the power-system area and several attempts have been made to combine these into one overall definition. Those attempts typically resulted in another definition. In this paper we will not attempt to add another definition of reliability further than stating that reliability concerns the performance of the system.

In the viewpoint of the authors, „reliability" is a subjective and qualitative term that has a different meaning for different players in the supply of electrical power. As we will see below a big difference in meaning exists between the network operator and the customer. But also different customers will have different viewpoints concerning the reliability of the supply. For example a small shopkeeper will have a different viewpoint from a domestic customer or from a large steel plant.

To obtain an objective and qualitative measure of the reliability it is necessary to introduce a number of „reliability indices". The definition of a reliability index should be such that there can be no doubt about its value. This will make sure that the different stakeholders can only agree on this value. By defining a sufficiently large set of reliability indices the discussion on the definition of reliability will be reduced to a discussion on the importance of the different reliability indices for describing the performance of the electric power supply.

An important part of the definition of almost any reliability index concerns answering the question: „What is an interruption?" A large part of the confusion concerning the term reliability can be traced back to the difference in the answer to this question.

2. THE VIEW OF THE NETWORK OPERATOR

The task of the network operator is to supply electrical energy to its customers for a reasonable price and with a reasonable reliability. The importance here is in the term „reasonable"; it requires some kind of trade-off between reliability and costs. As the reliability demands vary between different customers it is impossible to fulfil all customer demands; it would lead to unreasonably high costs for the other customers.

Another result of the requirement on reasonability is that the costs for measuring the reliability should not be excessively high. After all, most customers may not be interested in this information and therefore not be prepared to contribute to its costs. This is an important criterion in deciding on suitable reliability indices to be used by the network operator.

2.1. What is an Interruption?

The definition of a supply interruption as used by the network operator is based on Figure 1. Typically due to the occurrence of a short circuit or earthfault the circuit breaker opens and disconnects part of the customers from the supply. Traditionally the network operator does not keep a log of switching actions in the lower voltage levels of the system. A detailed log is typically only kept for the transmission system, but interruptions rarely originate there. The result is that the network operator is typically not aware that the supply to some of its customers is interrupted. Only

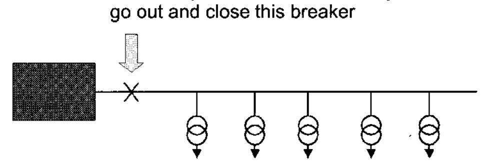

Fig. 1. Basic definition of supply interruption, as used by most network operators

when a customer reports the interruption, the network company can send a repair crew to remove the cause of the fault and close the breaker. The repair crew also makes a record of the interruption. If the breaker closes in an automatic way (as is the case with some protection schemes) often no record of it exists.

Any recordkeeping of interruptions with network operators is thus based on the termination of the interruption (the restoration of the supply), not on the start of the interruption (the loss of the supply).

From the network operator's viewpoint, an interruption is defined by the opening and closing of an interrupting device. In the example above, the interrupting device was the circuit breaker, but also other interrupting devices exist. The interruption starts when the interrupting device opens and ends when the interrupting device closes again. Another way of looking at it is by using the term "current interruption." An interruption is a situation in which no current flow is possible between the network and one or more of its customers; there is no galvanic connection during an interruption.

2.2. Short Interruptions

An important distinction among interruptions is between long and short interruptions. In most documents the distinction is based on their duration with typically limits between 1 minute and 5 minutes. The underlying reason for this distinction is however the difference between automatic restoration of the supply and manual restoration of the supply. The lower limit for long interruptions is chosen such that it is longer than the longest delay time for any automatic restoration scheme. In Sweden the longest delay time is 90 seconds so that the 3-minute lower limit for long interruptions fulfils this criterion. In the US some network operators use delay times up to almost 5 minutes, so that it was decided to use a lower limit of 5 minutes for a long interruption in IEEE Std.1366. Note that the terms „momentary interruption" and „sustained interruption" are used in IEEE 1366 instead of the IEC terms „short interruption" and „long interruption", respectively. Attempts have been made to define different types of interruption based on the reclosing process only, instead of on their duration. There are advantages in such an approach, but the current trend is to make a distinction based on duration.

There are a number of reasons, from the network operator viewpoint, to not report short interruptions. The two most important ones are:

- It would require additional investment in automatic registration equipment.
- The need for additional resporting and the need to install automatic systems.

Reporting of short interruptions may actually lead to a deterioration of the supply quality as network operators may decide that removing the autoreclosing scheme may lead to an overall costs reduction now that short interruptions lead to penalties and/or bad publicity. Any further discussion on this is important but outside of the scope of this paper.

2.3. Reliability Indices

The characterization of the supply performance has traditionally been based on two or three values:

- The number of interruptions per year;
- The sum of the duration of all interruptions during one year;
- The average duration of all the interruptions during one year.

As different network operators used widely different definitions an IEEE working group has set up a list of definitions for these and several other reliability indices. This resulted in IEEE Std.1366. No equivalent IEC document exists and an international working group (CIGRE/CIRED Joint Working Group C4.07) recently recommended the use of the IEEE indices for distribution systems. Here we will only give the definitions for the most commonly used indices.

For every long interruption (i.e. for every opening of an interrupting device lasting longer than a predefined lower limit, typically 3 minutes) a record is kept of the duration and the number of customers affected. From these records for all interruptions within the network during one year, the following reliability indices are calculated:

The „*System Average Interruption Frequency Index*" or SAIFI is defined as follows:

$$SAIFI = \frac{\sum_{i=1}^{I} K_i}{K} \tag{1}$$

with K_i the number of customers affected by interruption i, K the total number of customers served by this network operator, and I the number of interruptions originating within this network. The SAIFI index is obtained by adding the fraction of customers affected by each of the interruptions that take place during one year.

The „*System Average interruption Duration Index*" or SAIDI is defined as follows:

$$SAIDI = \frac{\sum_{i=1}^{I} D_i}{K} \qquad (2)$$

with D_i the duration of interruption i.

The "Customer Average Interruption Duration Index" or CAIDI is defined as follows:

$$CAIDI = \frac{SAIDI}{SAIFI} \qquad (3)$$

When interpreting these indices it is very important to realize that they give averages over all customers. The aim of these indices is to give a measure for the performance of the system for all customers. Consider the hypothetical case that a network operator suffers 10 interruptions during a year. Each interruption affects 10% of its customers; $\frac{K_i}{K} = 0.1$ in (1) and for every interruption this involves the same customers. The SAIFI value for this network operator is equal to 1 interruption per customer per year. However 90% of the customers do not experience any interruption whereas the remaining 10% of the customers experience 10 interruptions.

A number of additional indices has been introduced, e.g. "Customers Experiencing Multiple Interruptions" in IEEE Std.1366. This basically gives more information about the performance of the supply. But the basic issue remains, which is that a system index cannot provide information about an individual customer.

3. THE VIEW OF THE CUSTOMER

3.1. What is an Interruption?

For a customer an interruption occurs when the process driven by electricity stops or no longer performs as intended. The opening of an interrupting device (i.e. an interruption in the viewpoint of the network operator) will in the long term also lead to an interruption of the process as seen by the customer. The term "interruption of plant operation" was used by one of the authors several years ago to describe the customer viewpoint.

Defining an interruption from the customer viewpoint is much more difficult than from the network-operator viewpoint. Not only does it vary between customers it even differs with time for one customer. An example: somebody can cope with a one-hour interruption when working on a laptop but only with 200 ms when using the desktop. The same distinction can be made during off-work time, where the MP3-player has back-up power for several hours but the "classical" CD player or television for less than a second.The loss of light is not a problem at daytime but will make reading or writing very difficult in the evening.

Even though the impact on the process driven by electricity is what matters in the end, it is not an appropriate criterion to base a reliability index on. Such a reliability index would not be reproducible, not even for one and the same customer.

A more appropriate method is to base the interruption definition (the term „interruption criterion" is also used) on the voltage as experienced by the customer. To do this we have to introduce so-called „event indices". In the network-operator viewpoint an interruption was characterized by its duration and the number of customers affected. For an individual customer only the duration matters. There are also other power system events, which do not lead to a complete loss of the supply but merely to a reduction of the voltage at a customer location for a limited duration. This gives the „residual voltage" as a second characteristic. The definition of „residual voltage" is also not straightforward, especially not when it concerns measurements. Some of the issues involve the difference in voltage between the three phases and events for which the voltage magnitude varies with time. This discussion is outside of the scope of this paper. For more on the definition of residual voltage („magnitude" in the IEEE terminology) see IEC 61000-4-30 and the draft IEEE Std.1564.

The interruption criterion indicates which combinations of duration and residual voltage the customer tolerates and which ones not. An example of such a criterion is shown in Figure 2. Any event with voltage and duration above the green curve will not cause an interruption of plant (or process) operation. Only events below and to the right of the green curve are of concern for the customer.

A third area is indicated in Figure 2, where the impact of the event increases from a mere (economic) inconvenience to a dangerous situation. Such is for instance the case in the petrochemical industry. If the voltage does not recover within a few seconds the plant will go in an uncontrolled emergency shutdown. For shorter events the plant will still shut down, so that the economic costs are the

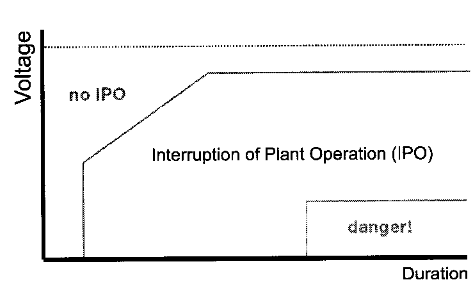

Fig. 2. Definition of interruption from the customer viewpoint; the green curve is generally referred to as the "immunity curve" or "voltage-tolerance curve"

same, but in a controlled and safer way.

A little bit of terminology is needed here. The following terms are used commonly in the power-quality literature: More on the differences and similarities between "reliability" and "power quality" later:

— A voltage dip (also known as "voltage sag") is an event with a reduced voltage during a limited time, for example 120 Volt (in a 230 Volt-system) during 250 ms.
— An interruption is an event with a voltage close to zero; typically an upper limit of 10% of the nominal (normal) voltage is used.
— A short interruption is an interruption with duration shorter than 3 minutes.
— A long interruption is an interruption with duration longer than 3 minutes.

Note the principal different in the definition of interruption as used here and as in the previous section. In the previous section an interruption was defined as a situation in which there cannot be any current flow from the network to one or more customers. Here an interruption is defined as a situation in which there is no voltage (a "voltage interruption"). In most cases these two definitions are equivalent, but for example with the introduction of local generation they will start to differ. Again, it is not the aim of this paper to favour any of these definitions, but only to point out the fundamental difference.

3.2. Reliability Indices

For one individual process, a convenient reliability index is the number of interruptions per year, where an interruption is defined as an event more severe than the immunity curve for that process. In other words: the reliability index gives the number of events per year with voltage and duration below the green curve in Figure 2. Such an approach would however require a dedicated index for each individual process. For assessing the compatibility between a process and the power supply, it is exactly this index that is calculated: See for example the excellent, but heavily underrated and misunderstood, IEEE Std.1346. To quantify the performance of the supply such an index would give very limited information however. Even one individual customer would typically require a number of indices, for the different processes (see the discussion before on the difference between working on the laptop and working on the desktop).

One approach to solve this problem is to define a "standard voltage-tolerance curve". Such a curve needs to be representative of typical equipment (or processes). Examples of such indices are the SARFI-CBEMA, SARFI-ITIC and SARFI-SEMI where the CBEMA, ITIC and SEMI curve, respectively are used as standard voltage-tolerance curve. One may see such a curve as a distinction between "dips that should not be a problem for most equipment" and "dips that may be a problem for equipment". The reliability index thus gives an upper limit for the expected number of times per year that typical equipment (a typical process) will mal-operate because of disturbances in the voltage. The advantage of this approach is that it results in a single number quantifying the supply performance. This "single-index approach" is heavily promoted in the US literature. Its disadvantage is however that it still gives limited information to the customer. It is a big step forward compared to only providing information on long interruptions (interruptions as defined by the network operator) but it does not allow the customer to estimate the impact of using equipment with improved immunity against voltage dips.

The alternative approach is to give the number of events as a function of their characteristics (voltage and duration being the most commonly-used characteristics for these events). There are a number of different ways of presenting this information, but the most-commonly used one is the so-called „voltage-dip table". See for example the draft IEEE Std.1564 or the final document of CIGRE/CIRED joint working group C4.07. An example of such a table is shown in Table 1. Each cell in the table gives the number of events per year within the range of residual voltage and duration indicated by the row and the column, respectively. For example, there were 7.7 events with a residual voltage between 70 and 85% of nominal and duration between 0.5 and 1 second.

Such a voltage-dip table can be seen as a way of quantifying the performance of the supply from the viewpoint of the customer. The customer could next choose an index that fits with the immunity of the process, as in the examples below. In both cases it is assumed that gives the number of events that can be

Table 1. Example of voltage-dip table (number of events per year within the given range of residual voltage and duration)

	0.02-0.1 s	0.1-0.5 s	0.5-1.0 s	1.0-3.0 s	3.0-20.0 s
85-90%	57.7	16.3	4.7	2.2	1.0
70-85%	85.5	42.8	7.7	2.4	0.3
40-70%	50.4	49.3	7.4	2.1	0.3
10-40%	19.7	40.3	5.0	1.9	0.3
0-10%	0	2.4	1.0	2.9	2.7

expected at the interface between the customer and the grid.

— **Example 1**: A sensitive production process stops whenever the voltage drops below 85% for longer than 100 ms. From it follows that this process will experience on average 168.8 interruptions (IPOs) per year. This equals the sum of all cells with the exception of the first row and the first column.

— **Example 2**: This number is seen as far too high and an investment in less sensitive equipment is considered. With this new equipment the process stops whenever the voltage drops below 70% for longer than 1 second. This results in on average 10.2 interruptions of process operation per year.

3.3. Power Quality versus Reliability

Another hot discussion point is the difference between power quality and reliability. The number of definitions on power quality may even be bigger than on reliability, so that we are really entering dangerous territory here.

Power quality concerns the interaction between the customer and the grid (or between equipment and the grid) via voltages and current. The interaction takes place through power-quality disturbances: deviations from the ideal voltage or current magnitude or waveform. Two types of disturbances can be distinguished: small and continuous disturbances, like small variations in frequency or voltage magnitude; and large sudden disturbances like interruptions and dips. The former are referred to as "*variations*", the latter as "*events*". The interaction can further be split in two parts again: the equipment or customer impacting the network through the current (*"current quality"*) and the network impacting the customer or equipment through the voltage ("*voltage quality*"). This makes that we can split power quality into four parts, as in Table 2. The bottom-right part ("voltage-quality events") corresponds to the above-mentioned reliability from the customer viewpoint. To get a complete picture, the above discussion for voltage dips and interruptions must be extended with other voltage-quality events as well. For industrial equipment, voltage swells and voltage transients may have to be considered.

Current-quality variations	Current-quality events
Voltage-quality variations	Voltage-quality events

Table 2. The four aspects of power quality

4. SITE AND SYSTEM INDICES

When quantifying the power quality (performance of the supply) a distinction is often made between "*site indices*" and "*system indices*". A site index quantifies the performance at one specific location in the system. In most power-quality studies the term is used for the location of a power-quality monitor or another measurement device. A site index may also refer to the quality as perceived by one specific customer or one specific piece of equipment. This interpretation of a site index is the same as the reliability in the viewpoint of the customer as in Chapter 3 of this document.

A system index is obtained as a statistical representative value from the site indices over a number of sites spread through a system. The sites under consideration are, in power-quality surveys, the locations of measurement equipment. However, for the purpose of our discussion on reliability, the sites should be considered as the locations of the individual customers.

Example: assume that the SARFI-ITIC values are known for each customer. (Obtaining this information is a different issue, outside of the scope of this document.) A possible site index is the average of all site indices. Alternatively a weighted average can be used, were the weighting factor is proportional to the annual energy consumption of the customer. In some publications the 95% value is preferred above the average value.

Consider as a site index the number of long interruptions and as a system index the average number of long interruptions over all customers supplied from the network.

$$N_{SYS} = \frac{\sum_{k=1}^{K} N_k}{K} \quad (4)$$

with N_k the number of long interruptions experienced by customer k and K the total number of customers. Compare this with the reliability index used by the network operator: SAIFI as in (1). The first difference is in the definition of interruption, but we will assume that the two definitions give the same results. In other words: opening the interrupting device without automatic restoration is equivalent to zero voltage for the customer for longer than 3 minutes. The remaining difference is only in the order in which the events are counted. This is explained by using the hypothetical example in Table 3. In this example the network operator supplies 32 customers and the supply to one or more customers was interrupted 12 times. When calculating the SAIFI value as in (1) first the number of customers affected by each

Int.	Customers affected																													No/cust
1																														13
2																														10
3																														7
4																														9
5																														4
6																														8
7																														7
8																														6
9																														8
10																														3
11																														2
12																														9
No/int	2	2	3	3	3	3	4	4	4	3	3	4	4	5	5	5	3	3	3	3	2	2	2	3	3	3	1	1	0	0	0	86

Table 3. Hypothetical example of interruptions and customers affected

interruption is counted (the number of dark cells per row). These values are next added for all the interruptions. Calculating the system index as in (4) implies that the number of interruptions per customers is first calculated (the number of dark cells per column) after which the sum is taken over all customers.

Thus both (1) and (4) result in the same value (the number of dark cells in the table, 86, divided by the number of customers, 23, gives 3.7 interruptions per customer per year). This leads to an interesting conclusion. *The index used by the network operator to quantify the reliability is the same as the average of the indices used by the customers to quantify the reliability, as long as an equivalent definition of interruption applies.* Using a number of different definitions of interruptions may solve the problem of the different interpretations of reliability. Of course referring to all of those as "interruption" will only lead to confusion, so that we need to introduce some alternative terminology. Where this in the end will lead to remains to be seen, but in the opinion of the authors a voltage-dip table averaged over all customers would be an appropriate index for voltage dips and short interruptions next to the SAIFI index for long interruptions. This conclusion however does not address the basic issue that network operator and customer use different definitions for interruption. This will be addressed in the next section.

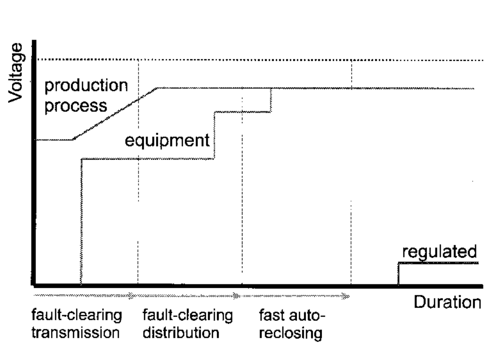

Fig. 3. The gap between interruption definitions as used by the customer and by the network operator. The equipment curve is based on IEC 61000-4-11;the production process is often more sensitive than the equipment; the regulated curve starts at 3 minutes duration

5. THE COMPATIBILITY GAP

In the existing structure of the electricity market, the network operator is becoming more and more under the control by a regulatory body. This regulatory body decides among others the reliability indices that the network operator should publish. In several countries the resulting values are used in the setting of the price to be charged to the customers of the network operators. In all these countries only interruptions longer than three minutes (long interruptions) are considered in the price-regulation. The definition of interruption used by the network operator is thus determined by the regulatory body and in all known cases equal to events of 3 minutes and longer.

Equipment and production processes are however sensitive to much shorter and more shallow events, starting at 100 ms or lower. The resulting "compatibility gap" is shown in Figure 3. With reference to the discussion in the previous chapter, this makes that the reliability index used by the network operator has no relation at all to the system index obtained by averaging the reliability/quality indices for individual customers. This is an issue that especially concerns industrial customers. Not only is their equipment more sensitive to short-duration disturbances, the impact is also typically much bigger than for domestic customers.

There are a number of reasons used by the regulatory bodies for only considering long interruptions. One of the reasons is that measuring short interruptions and voltage dips for all customers would require a large investment in monitoring equipment; the majority of customers (i.e. the domestic customers) are not seriously affected by voltage dips; customers not affected by dips are not willing to pay for the data collection. The result is however that industrial customers (small in number, large in energy consumption) feel not represented by the regulatory bodies.

A more desirable situation is the one shown in Figure 4 where regulation takes place for those events for which equipment may be sensitive. A curve has been agreed in this case to distinguish between those events for which the network operator is responsible and those events for which the customer (or the equipment manufacturer) is responsible. Such a responsibility sharing is already in place for variations (where terms as "compatibility level" and "voltage characteristic" are used) but not yet for events. Local agreements could be made, but recommendations or standards by an international organisation would have a wider impact and could trigger such local agreements.

6. WHAT ARE SUITABLE INDICES?

In the earlier parts of this paper the two different viewpoints on reliability have been presented. It was also emphasized that a discussion on reliability can only lead to useful results if appropriate reliability or power-quality indices are defined. That leaves open the question on what are suitable indices. Answering that question is far beyond the scope of this paper, but some thoughts will still be presented.

The basic thought is that a reliability index should be a quantification of the performance of the network. As the network is there for the customers, an improvement of the index should correspond to an improvement of the supply to the customers. Note that an improvement may be a reduction or increase in value depending on the type of index.

Indices by themselves have no value. Indices only become of value when they are used as a feedback signal to the design and operation of the supply to the customers. This may be internal or external use by the network operator, but it should always be aimed at improving the performance.

To define an index for one individual customer is relatively easy. But even here the relations between the different aspects of the reliability and the performance is not always clear. For industrial and commercial customers a link can be made to production stoppages or to financial losses. For domestic customers a kind of customer satisfaction needs to be considered. Aspects to be included are the number of events per year (10 events per year are worse than 1 event per year) and the event characteristics like duration and residual voltage (a 3-day interruption is worse than a 20-minute interruption), but also the spread of events through the year. A customer with 10 events per year will be affected in a different way when those events all occur during one afternoon than when they occur randomly through the year.

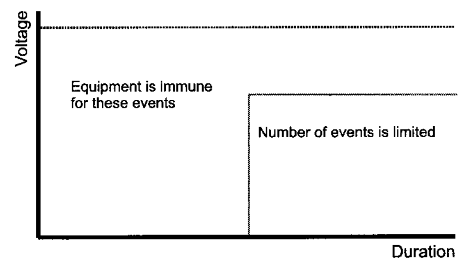

Fig. 4. The same demand on network operator and industrial customer: the compatibility curve has disappeared

Two examples will be given of the use of indices that resulted in a deterioration of the supply while the indices improved. A rather classical example is the use of autoreclosing together with fuse saving. This results in a reduction of the number of long interruptions by 80 to 90% and thus in a huge reduction in SAIFI and CAIDI. The customer will however be exposed to more short interruptions and customers sensitive to short interruptions will experience an increase in the number of interruptions (of plant operation). Note that it is not the autoreclosing scheme that causes the deterioration of the supply performance but its combination with a fuse-saving scheme.

A second, less obvious, example concerns the dip frequency. For most customers, the majority of dips are associated with faults due to adverse-weather. Next to that, dips occur due to other fault causes like equipment failures. Addressing the lightning related dips will give a significant reduction in the number of dips and if all other parameters are kept the same this is an improvement of the supply. But the improvement may not be big as suggested by the reduction in dip frequency. Lightning storms have a limited duration, typically a few hours, and the restoration of the production process takes in many cases longer than the duration of the storm. The result is that all dips during one storm at most lead to one production stoppage. The heavily-discussed concept of "time aggregation" has been introduced to correct for this. After time-aggregation lightning-caused dips will have a much smaller contribution to the dip frequency and the more randomly-occurring dips may dominate the statistics. If money is moved from line maintenance to lightning mitigation, the customer may even experience a deterioration of the supply.

All this was just for individual customers ("site indices"). Defining indices to quantify the performance of a whole network is even more difficult. A kind of statistically-relevent value for all customers is needed. This requires considerations that are no longer based on engineering but on political decisions. An important point of discussion will be the weighting between industrial, commercial and domestic customers, where it has to be accepted that no system index will be able to cover the requirements of all customers.

7. CONCLUSIONS

By addressing the different viewpoints on reliability, better insight is obtained in the different requirements and consequences of power-system events for network operators and especially industrial customers. For both the network operator and the customer it is the restoration action that defines an interruption. But the restoration actions do not necessarily occur for the same underlying event in the power system. The result is that the two sides use different definitions of the term interruption and thus have a different viewpoint on reliability. This makes communication more difficult.

It is recommended to refrain from using the terms "reliability" and "interruption" in qualitative discussions but instead use well-defined reliability and/or power-quality indices. It is shown that the standard method for calculating the SAIFI index (number of interruptions per customer per year) will result in the same value as when averaging site indices over all customers, under the assumption that an equivalent definition of interruption is used.

A compatibility gap exists between the demands placed, by the regulator, on the network operator and the demands placed especially on the industrial customer by the susceptibility of the equipment and the production process to voltage dips.

A local, national, or international agreement is needed on a responsibility sharing such that this compatibility gap disappears.

System performance indices have to be based on the performance requirements of individual customers, even though the system index can never cover the requirements of all customers.

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