

# POWER QUALITY: MEASUREMENTS OF SAGS AND INTERRUPTIONS

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Good power quality refers to the condition where a uniform constant magnitude sinusoidal fundamental frequency voltage is seen by the customer. Poor power quality takes on some notably different concepts: a) harmonic content of the system voltages, as well as the currents, b) voltage interruptions and sags and the related concept of flicker, and c) voltage surges. This paper will focus on issue b.

Over time, small home electronics devices have gradually improved in their ability to withstand the short duration interruptions or sags that lead to blinking clocks and lost microcontroller programming, but including good versions of this feature competes with consumer demand for low price, so the matter will never be perfected. Further, if the home electronics requires any substantial power to run, such as computers, lighting, or entertainment equipment, the customer will need a small UPS to maintain operation. The industrial customer also faces rapid shutdown of a process for interruptions or sags. While a UPS is needed for high power equipment or longer events, most issues could be resolved if the facility could ride through interruptions of a second or less in duration. The usual worst source of problems is with the control system's motor and lighting contactors which, in typical design, drop out if voltage drops below around 50-75% for more than 1-2 cycles. Other culprits that can lead to shutdown for short voltage sags and interruptions include computers, PLCs, and miscellaneous support equipment such as the electronics associated with some sensors and gauges.

We will review the typical interruption measurements. Utilities have a long-standing practice of monitoring for the longer duration interruptions. These are important incidents that can lead to issues such as food spoilage due to lack of refrigeration, street light outages leading to traffic accidents, lost work time, closing of production lines in industrial processes, etc. However, the U.S. market has become accustomed to high availability of power and has rising expectations. It does not want the "glitches" either. Utilities do not monitor the shorter interruptions and sags as thoroughly as the long term events. These interruptions and sags, due to their frequency and ensuing process restarts and resets, actually may be the greater issue to the majority of customers.

## Typical Equipment Sag and Interrupt Withstand

### ITIC Curve

The Information Technology Industry Council (ITIC) voltage withstand curve, figure 1, has been widely publicized and appears to be the main reference in multiple papers and other standards as a measure of good power quality for computers and business electronics. The curve is distributed at the website given in reference [1]. If one obtains the figure from the site referenced in [1], one will find some explanatory text associated with it.

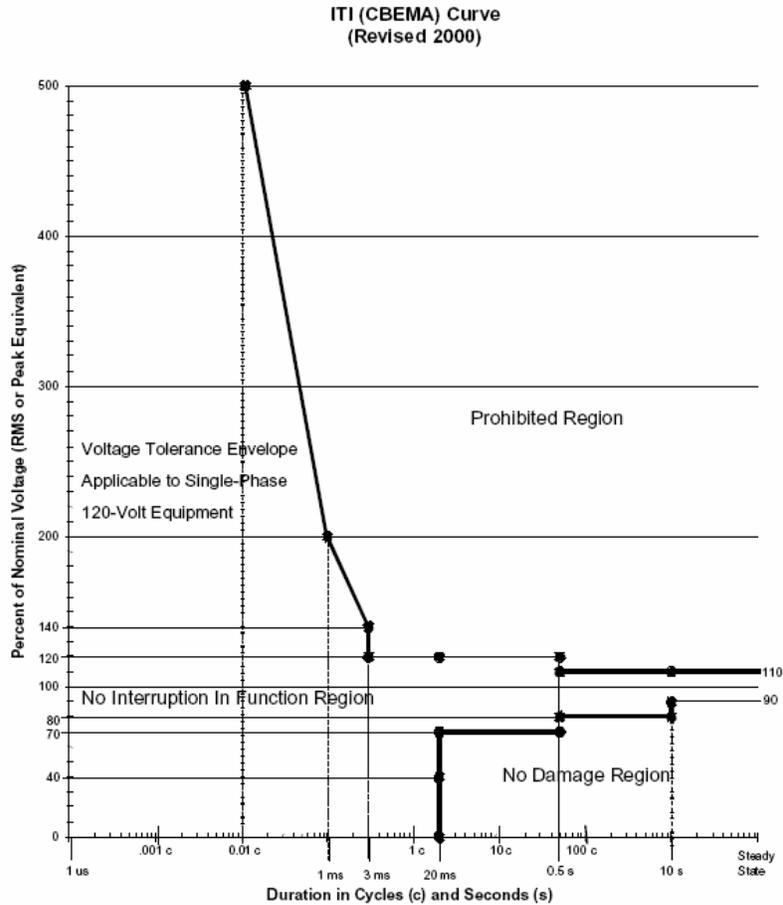


Figure 1: ITIC-2000 Curve [1]

Figure 1 is commonly referred to as the ITIC curve, though it still contains reference to CBEMA. There are two older varieties of this curve, figure 2a and 2b, that can be found in various papers. The curve in figure 2a was published in the 1980's by the predecessor to ITIC, the Computer and Electronics Business Manufacturers Association (CBEMA), and it is more commonly referred to as the CBEMA curve. The curve in figure 2a is hard to work with because its boundaries are not rigidly defined by equations. The curve in figure 2b was published in the mid 1990's and is basically the same as figure 1, but it is missing some details that make figure 1 easier to read. (The author of this paper has seen versions of 2b that have the time markings seen in Figure 1, but it is unclear if these marks were in the original document or added by subsequent authors.) The author of this paper does not know where "official" copies of the curves in figure 2 could be obtained. The CBEMA curve in figure 2a still shows up in many texts but appears to be out of print by the original source and available mainly as a hand-me-down from one paper to another. The copies of the curves in figure 2 are cut and pasted from reference [2] (a freely published document from Power Systems Engineering Research Center, [www.pserc.org](http://www.pserc.org)).

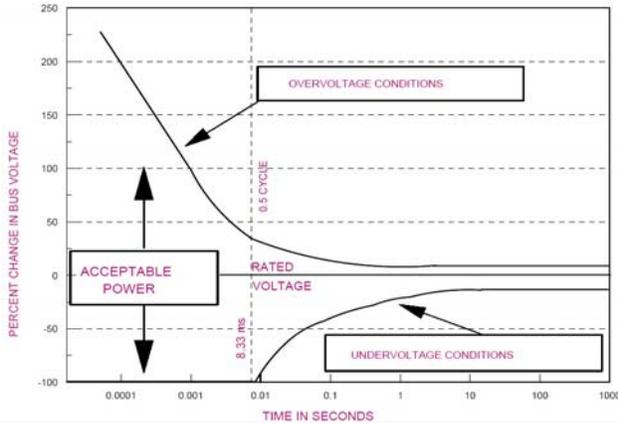


Figure 2a: Old CBEMA

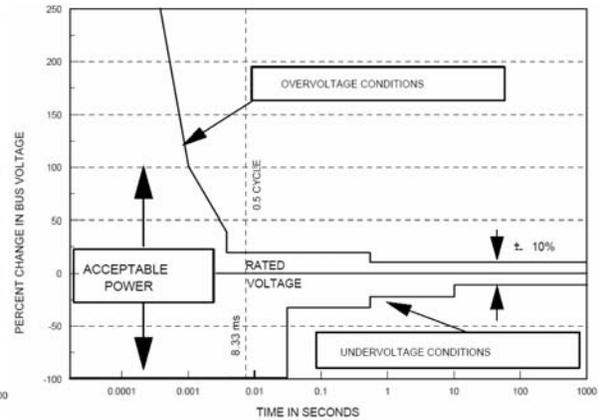


Figure 2b: Old ITIC Curve

### SEMI F47

The Semiconductor Equipment and Materials International (SEMI) organization lobbies and creates standards for the semiconductor industry. The chip manufacturing business faces very high costs during voltage interruptions and, as a result, chip factories make large investments in developing systems that are resistant to the more common short power interruption or sag. The SEMI standard SEMI-F47 [3] defines a target tolerance curve for AC interruption and sag withstand that equipment in the plant should be able to withstand without a shutdown. SEMI F47 specifies tolerance over the time from 0.05s to 1.0s. In figure 3, the ITIC data has been included in the dashed line extending outside this time frame. The F47 tolerance is tighter than the ITIC curve over the period of 0.05 to 0.2s. See the publicly available reference [4] (by semiconductor industry consortium SEMATECH) for an overview of semiconductor plant concerns.

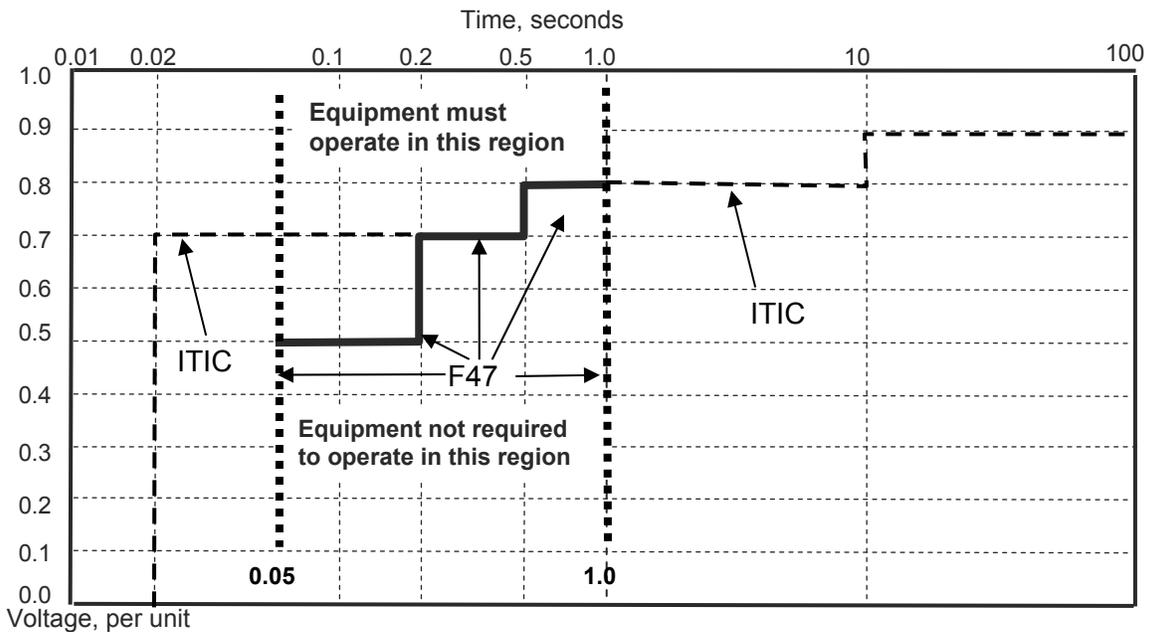


Figure 3: SEMI F47 Curve [4], 0.05-1.0s, with ITIC Curve (dashed)

## Motor and Lighting Contactors

The leading reason for the inability of a facility to ride through very short interruptions and sags is rapid dropout of electrically held contactors. Electrically held contactors typically are designed to be just barely held in place, so that there is a rapid fail-safe dropout of the contactor when the control system or operator determines the device must be shut down and then removes contactor control voltage. Typical contactors drop out at 65% voltage and in 25ms (1-2 cycles) for full voltage removal, though this ranges from 40%-80% voltage and 15-200ms. Some manufacturers have available contactors with low dropout voltages or auxiliary hold-up devices that allow the contactor to hold up with lower voltages and react more slowly to loss of voltages. These devices must be specified; they are not commonly supplied. Figure 4, taken from the product's sales brochure, shows how a contactor holdup device, the SquareD™ LVRT™, allows for fairly low voltage operation. The dotted lines showing typical contactor dropout ranges were added by the author of this paper; they were not in the original source document. (Disclaimer: This figure may not represent latest design, please consult with SquareD™ for more complete and up-to-date information on this device. Also, other manufacturers have answers to the issue of low voltage dropout concerns; this is only supplied as an example of how the issue may be addressed.)

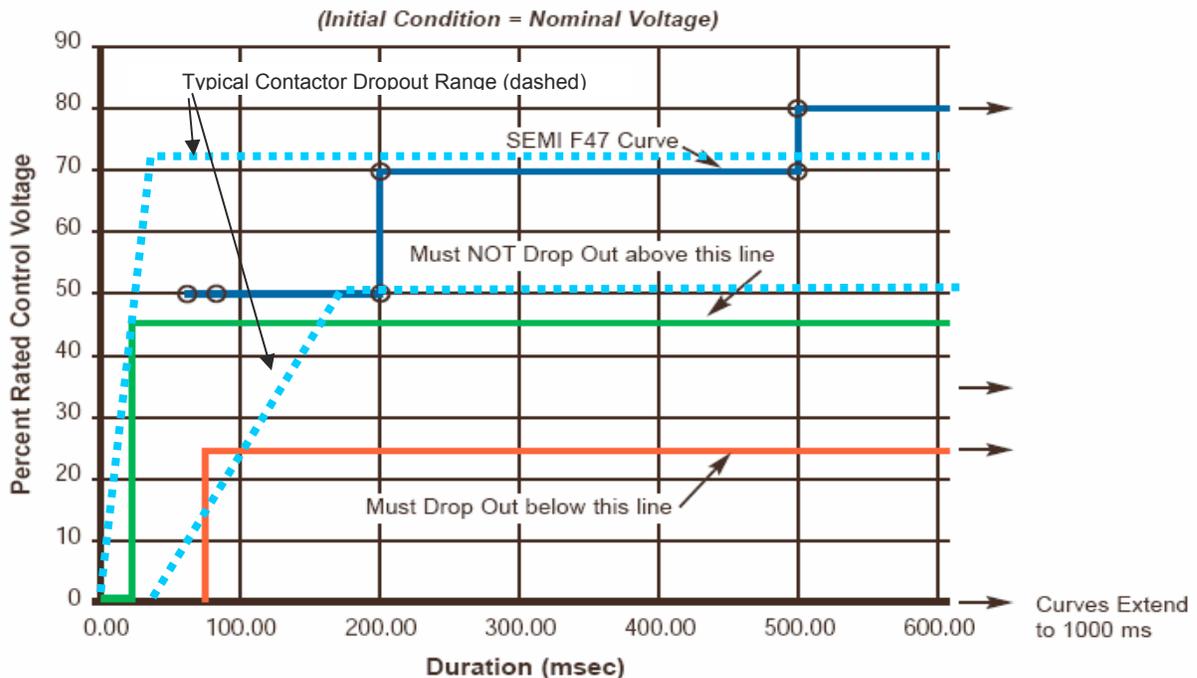
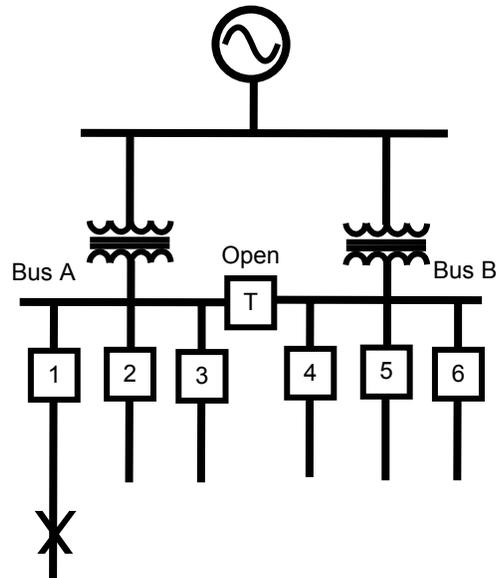


Figure 4: SquareD™ LVRT™ Module (Contactor Add-On Device for LV withstand), and more typical contactor dropout voltages (dashed line), added by this paper's author.

## Fault Tolerant Power Systems

A fault in the typical radial distribution power system causes voltage disturbance effects over a wide area. The fault in figure 5, of course, affects the customers on the line, but the current in the fault also causes a voltage drop across the transformer, so every feeder on bus A also sees the fault. There is a voltage divider effect: The voltage degradation at bus A is the ratio of the line 1 impedance ( $Z_{Line}$ ) and the total fault impedance ( $Z_{Line} + Z_{Xfmr} + Z_{System}$ ). There is little that the

utility can do to change this effect except for transformer or line replacement. The larger the substation transformer, the more customers and feeders will be fed by that transformer, so the more chance there will be that faults can affect multiple other customers. Many small transformers, each feeding fewer feeders and a dedicated transformer to the sensitive customer would be a way to reduce this issue, but this is a more costly way to deliver power.



*Figure 5 - Typical Utility Distribution System, with fault*

Transmission system faults will bring the entire substation down and, again, this is a fact of the power system that the utility has limited ability to change. A saving factor though, and the reason large customers may want to be on a transmission level connection, is that transmission line protective relaying is very high speed, due to end-to-end communication aided tripping schemes and high cost high end protective relaying. Further, due to the networked nature of the transmission system with multiple feeds to the substation and very high speed reclosing in most cases, the loss of one line does not cause an extended blackout to the station. Power interruptions or sags are very short at the transmission level, in the under 0.3 second range for almost all faults (caveat: substations on “tapped lines” may see longer and more interruptions).

The utility can use designs and work at the radial distribution level to prevent the fault from occurring including ideas such as those below, but in all cases there are economic costs and the return on the investment is hard to quantify.

- Aggressive tree trimming
- Animal deterrent designs (animal shields, greater spacing between conductors and to ground, longer bushings, etc.)
- Underground construction
- Replacing near end-of-life equipment, before it fails
- Patrols looking for problem equipment
- Lightning resistant line arrangements
- Use single pole reclosers
- A close analysis of fuse saving vs. fuse blowing schemes (a marginally successful idea that tries to prevent fuse operation at the expense of interrupting power to more customers for a short time)

## Protective Relaying, Reclosing, and Power Restoration Speeds

Some may wonder if the utility can restore power fast enough to prevent the industrial facility or homeowner from seeing the interruption or sag. Actually, it is not very feasible without special designs for which the sensitive customer must pay highly. Protective relays take at least one cycle to sense a fault but typically, in the distribution world where time-overcurrent relaying is ubiquitous, substantially longer, reaching to the order of a second or two. If the facility manages to survive the time frame of waiting for the overcurrent element to clear the fault, waiting for a high speed reclose still will leave the plant without power for about 0.25-0.5 seconds. The reclose may be just fast enough to prevent shutting down of the facility given the approach used by SEMI-F47 compliant facilities but, otherwise, comparing these times to the dropout of the typical contactor and the ITIC curve, it can be seen that one should not have extensive hope. Without special fault tolerant facility designs, it may be advisable to utilize slower reclosing because, if the facility is already shutting down, there is a risk of damage from restarting things that are in a shutdown mode, such as motors with any residual field.

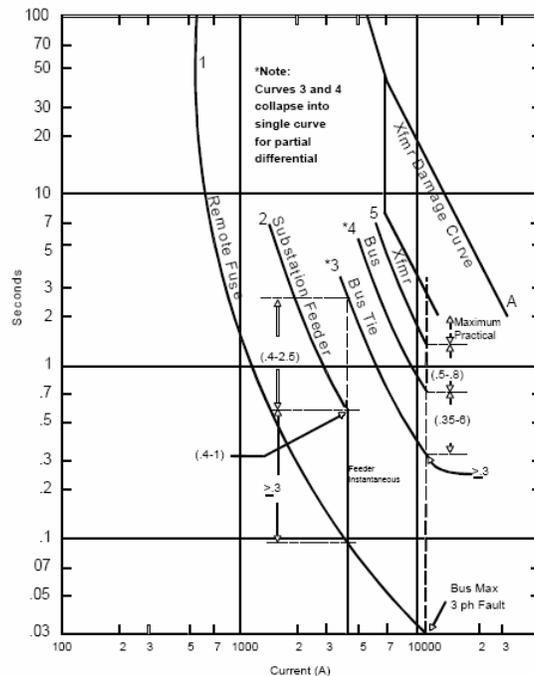


Figure 6 - Typical Time Overcurrent Coordination Curve

If the facility needs faster fault recovery and a smaller period of bad voltage, then dedicated auto-transfer schemes, fed from two different substation transformers, must be put in place, where transfer times in the 100-150ms time frame can be obtained.

As previously noted, transmission system faults are cleared much faster than distribution system faults due to high cost communication aided protection schemes. In reference [4], and also found on the EPRI-PEAC web site ([www.epri-peac.com](http://www.epri-peac.com)), there is a scatter plot of a large number of interruptions seen by semiconductor facilities. Note that this would be indicative of the voltage profile that utilities provide to some of their most sensitive customers, likely with most being fed from transmission systems where fault clearing time is very fast.

Radial distribution systems will see far more transient interruptions and sags than long term interruptions. A long term interruption and sag monitoring project was funded by EPRI to in the mid 1990s. It closely monitored 100 feeders around the country. The results are used for commercial purposes and all published articles are copyrighted, so the results cannot be extensively repeated in this paper. A great amount of data from this study, and others, is found in [5] and [6]. A copy of [5] is available on the EPRI-PEAC web site (at the time this paper was written). As a very brief summary, the papers support the concept that the typical distribution system has many more sags than complete interruptions and more short interruptions than long interruptions. The published reports tend to indicate that the number of sags where voltage dropped to between 70% and 10% of nominal outnumbered the total interruptions by a factor of about 3, and the number of short interruptions lasting less than 10s exceeded the number of interruptions greater than 10 seconds by a factor of about 2.

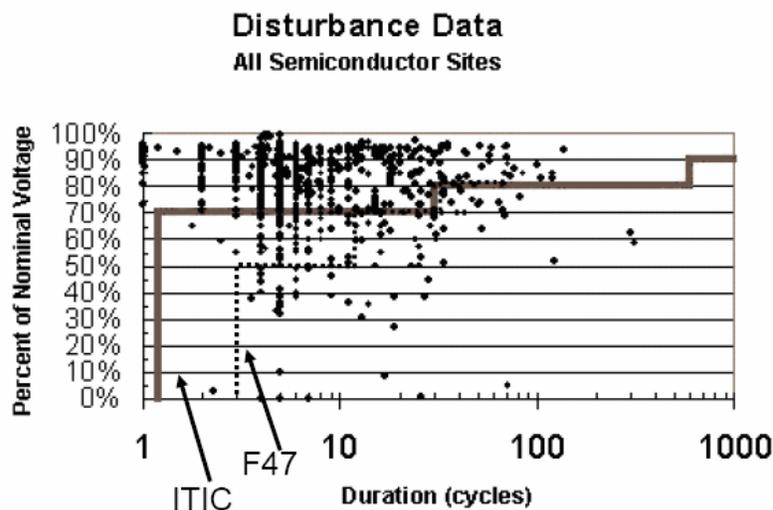


Figure 7 - Scatter Plot of Semiconductor Facility Sags and Interruptions [4]

## Indices of Long Term and Short Term Interruptions and Sags

### Long Term Sustained Interruptions (Reliability Indices)

Long term interruption measurements are referred to as Reliability Indices. Since there are many more sags and short duration events, these indices are capturing the gross issues. Though each utility may have a variation in the minimum interruption time that is looked at by the reliability indices that are used, the general idea is that these are events where voltage has dropped to 0 for around 1-5 minutes. This typically means the normal automatic voltage restoration schemes have failed to restore power, and all short term options available to SCADA controls, system operators, or on-site personnel to restore power have been exercised. Manual intervention or equipment repair has become necessary.

A freely available paper that reviews the common reliability indices is reference [7], but much information about them can also be found with a certain level of web browsing. A very complete reference for those with some money to spend is reference [8], where many common and not-so-common indices are described, along with examples of calculation methods.

These indices are frequently broken down between “All interruptions” and “Excluding major storms.” On one hand major storms can be a real issue that can offset a utility’s reliability index, but on the other hand how does one separate out the normal conditions from the unusual and stop the temptation to include too many events in the major storm category? There is an analysis in [8] on what constitutes major storms that tries to remove the matter from the subjective realm. The storm interruption data is compared to a multi-year statistical average of interruptions. The topic is too involved to discuss here.

**SAIDI:** System Average Interruption Duration Index = the net total time (hours or minutes) per year that the average customer is without power, counting only the sustained interruptions. In the USA, the number is typically on the order of 2-3 hours for all interruptions, and around 1-2 hours excluding major storms.

$$\text{SAIDI} = \frac{\text{Total of All Customer Interruption Durations (Sustained)}}{\text{Total Number of Customers Served}}$$

**SAIFI:** System Average Interruption Frequency Index = the number of times per year that the average customer sees a sustained interruption. The number is typically on the order of 2-3 for all interruptions, and 1-2 excluding major storms.

$$\text{SAIFI} = \frac{\text{Total Number of Customer Interruptions (Sustained)}}{\text{Total Number of Customers Served}}$$

**CAIDI:** Customer Average Interruption Duration Index = average time of a sustained interruption; i.e., the repair time for sustained interruptions.

$$\text{CAIDI} = \frac{\text{Total of all Customer Interruption Durations (Sustained)}}{\text{Total Number of Customer Interruptions (Sustained)}} = \frac{\text{SAIDI}}{\text{SAIFI}}$$

**ASAI:** Average Service Availability Index = the per unit availability of the power system. This is a positive spin to SAIDI. This is the total hours in the year the power system is available to the average customer, divided by the total hours in the year.

$$\begin{aligned} \text{ASAI} &= \frac{\text{Hours Service is Available to Average Customer in Year}}{\text{Hours in Year}} \\ &= \frac{8760 \square \text{SAIDI}}{8760} \text{ (normal year)} \\ &= \frac{8784 \square \text{SAIDI}}{8784} \text{ (leap year)} \end{aligned}$$

It is worth noting how spoiled this makes the average US customer look. With this index, if SAIDI is 2 hours for the year, the ASAI is 0.99977. However, this does not mean the same customer did not have issues with frequent short interruptions or sags that caused frustration at the facility or home.

**Less Common Interruption Measurements:**

Some less common measures are listed in [8]. These measures include:

**CTAIDI:** Similar to CAIDI, but denominator counts customers with multiple interruptions only once.

**CAIFI:** (Total number of customers interrupted)/(number of customers interrupted once or more). Note this is a measure of “If someone was interrupted at least once, how many net interruptions have we seen?”

**CEMI<sub>N</sub>:** (Total number of customers that experience more than N sustained interruption)/(Total number of customers served). This is similar to CAIDI, but denominator counts customers with multiple interruptions only once)

**ASIFI, ASIDI:** Similar to SAIFI and SAIDI, but interrupted load and total connected load is used in the calculations.

### **Momentary Interruption Measurements**

Momentary interruptions on one hand are those less than long term interruption, of course, but the matter is broken down a bit more finely in reference [9], IEEE 1159, to these categories:

- Voltage level
  - Interruption (<0.1pu)
  - Sag (0.1-0.9 pu)
  - Swell (> 1.1-1.4 pu)
  - Undervoltage (0.8-0.9 pu, > 1 Min)
  - Overvoltage (1.1-1.2 pu, > 1 Min)
- Time Frame:
  - Instantaneous (0.5-30 cycles) (does not apply to interruptions)
  - Momentary (30 cycles – 3 seconds) (the standard shows interruptions 0.5-3s categorized as momentary)
  - Temporary (3 seconds – 1 Min)
  - Long Term (> 1 Min)

Reference [8] gives some measures of momentary interruption measurements, but it stops short of giving measurements of sags. References [10] and [11] give guidelines on sag indices. Reference [11] is a future standard still in draft mode. A very early draft copy was available on the indicated web site at the time this paper was written.

**MAIFI:** Momentary Average Interruption Frequency Index = the number of times per year that the average customer sees any interruption. The number is typically on the order of 10-15 for all interruptions and 10 excluding major storms.

$$\text{MAIFI} = \frac{\text{Sum of All Customer Interruptions (Momentary Variety)}}{\text{Total Number of Customers Served}}$$

There is an unclear aspect regarding how the reclose process is counted. If a customer sees a trip, reclose, trip, and then a successful reclose, is the number of momentary interruptions one or two? The above definition is used in [8] to say that the count would be 2, and then [8] defines a second measure called **MAIFI<sub>E</sub>** (E for event) that would call this one event, and the MAIFI<sub>E</sub> would be 1. It is not clear what the average utility is doing in this regard. MAIFI counts are not easy to track and per [8], about 20% of the surveyed utilities track MAIFI, compared to more than 80% tracking SAIDI, SAIFI, and CAIFI.

### **Sag Measurements**

In various articles, such as [5], and [10], and the draft versions of [11], there are references to measuring voltage sags by the basic concept of how low the voltage goes and how long it stays there, assuming a relatively square shape to the voltage wave form. This is used to create “SARFI<sub>x</sub>” measurements. These measurements plot RMS excursions against some reference

value,  $x$ . There are a few references to using the fundamental frequency value rather than the RMS value, which allows the monitoring device to extract the voltage phasor data which in turn allows voltage phase shifts and sequence component voltages to be monitored as well. There are other measures besides simple voltage difference that are being considered for inclusion in [11], but until that standard is released and then put into practice, the common means of measuring voltage sag events appears to be mainly as follows.

**SARFI<sub>x</sub>**: System Average RMS (Variation) Frequency Index

The ratio  $V_{PU} = V_{RMS}/V_{NOM}$  is measured. Any time the voltage goes below the threshold defined by “ $x$ ”, the time duration is tracked. A table of excursions and their time frames is created. The value for  $x$  is commonly in undervoltage percentages: 90, 80, 70, 50, and 10. Overvoltage levels can also be tracked: 110, 120, and 140.

An effort to give some range to the time duration of the event can result in these indices:

**SIARFI<sub>x</sub>**: System Instantaneous Average RMS (Variation) Frequency Index

This is the same index as SARFI, but is limited to events that last from 0.5-30 cycles.

**SMARFI<sub>x</sub>**: System Momentary Average RMS (Variation) Frequency Index

This is the same index as SARFI, but is limited to events that last from 30 cycles to 3 seconds.

**STARFI<sub>x</sub>**: System Temporary Average RMS (Variation) Frequency Index

This is the same index as SARFI, but is limited to events that last from 3 seconds to 60 seconds.

**SARFI<sub>ITIC</sub>**: System Average RMS (Variation) Frequency Index-ITIC Limited

This is a complex time vs. voltage event that compares each voltage to the ITIC curve and registers deviation events when the ITIC curve is exceeded.

**SARFI<sub>F47</sub>**: System Average RMS (Variation) Frequency Index-F47 Limited

This is a complex time vs. voltage event that compares each voltage to the SEMI-F47 curve and registers deviation events when the F47 curve is exceeded.

Issues:

- There are three phase to phase voltages and three phase to neutral voltages. Which should be tracked?
- If one phase goes to a lower voltage than the other, do you report only the worst?
- For three phase customers, do you trigger an event when one phase goes low, or do you use some combination of the phases? Would it be satisfactory to lump the multiple voltages into one measuring algorithm (e.g. trigger off of  $V_{AVG} = (V_{AN}+V_{BN}+V_{CN})/3?$ ), or maybe use sequence component voltages such as “Drop in  $V_1$ ” or “Rise in  $V_2$  or  $V_0$ ”?
- Sometimes faults can cause a sudden shift in phase angle of one or two phases, creating equipment problems, yet RMS measuring loses this phase shift data.
- Would monitoring sequence component voltages ( $V_1, V_2, V_0$ ) be of value?
- If there is a notable change in voltage magnitude during the event, the event becomes hard to categorize.
- $V_{NOM}$  may be hard to specify in the transmission environment, where voltages are not as well regulated as on the distribution system. A “sliding scale” reference may be needed. Reference [11] appears propose a 1 minute voltage averaging technique as an optional voltage reference.

- Voltage degradation effects are not linear; e.g, if V goes below about 75% of nominal, many devices are facing a precipice and will rapidly shut down. At 75%, the next 5% drop may cause far worse effects than the last 5% drop. Some propose using an exponent on the voltage loss so that the farther the voltage excursion, the faster the index would increase.

## Flicker

Flicker is associated with voltage sags, but the matter is not as easily measured. The voltage magnitude itself is not the issue. The issue is that the rise and fall of voltage causes equipment, especially incandescent lighting, to pulsate. The measurement process is convoluted since one has to mimic equipment (lighting mainly) response, and the subsequent human eye and brain response and perceptions. Concepts such as shown in figure 8, from IEC standard IEC 61000-4-1 are required, and the resultant equations that the meter has to work with are not intuitively obvious to this paper's author.

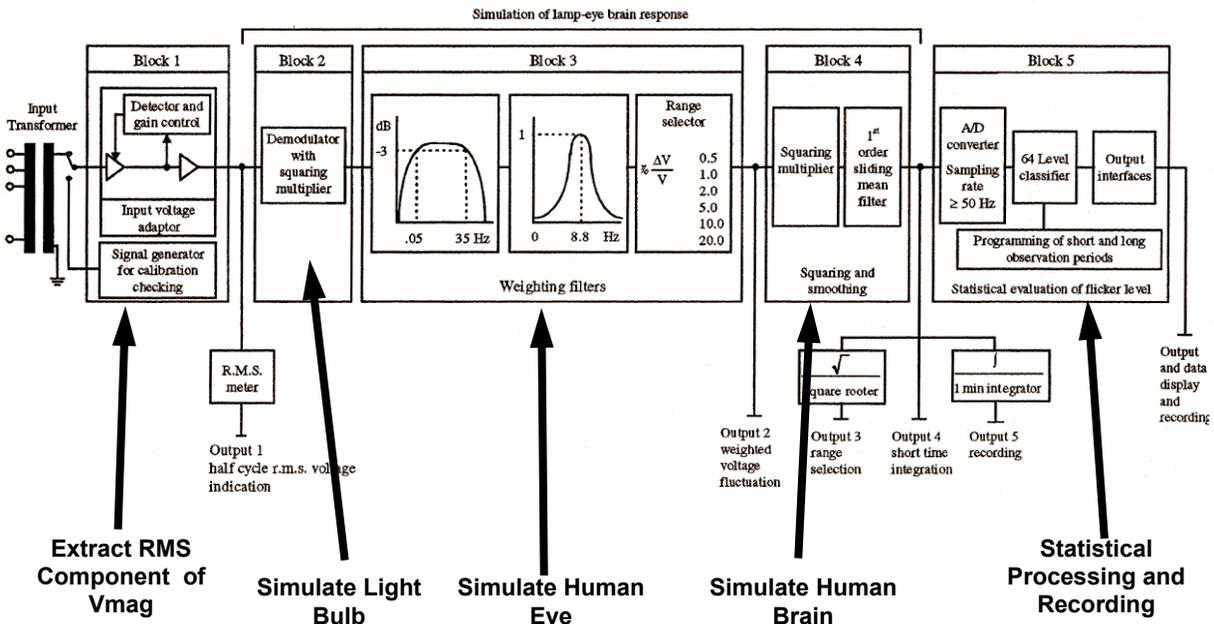


Figure 8: IEC 61000-4-15 Flicker Meter Block Diagram

## Monitoring with Relays and Meters

One of the motivations of this paper was to ask if these measures of power quality would have a role being placed in the meters and protective relays at the entrances to customer facilities. The existence of this measurement in the relays and meters will not occur until the general end user is aware of the measurement techniques and asks for the measurement to be available in the meters and protective relays.

## References:

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