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PENS Outage-Reliability-Stability-Quality (PENS-ORSQ) and GridCON
The PENS Power Intelligence Indexes

(For GridCON Report version1.20)
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0. Executive Summary

This report describes the motivation and methodology behind Gridmetrics' PENS-ORSQ and GridCON products. Mathematical details are given in appendices.

1. Index Description

In this section we describe the procedures behind the PENS-ORSQ and GridCON methodology.

The key to understanding PENS-ORSQ and GridCON are its four components. First, is the outage given by POI, the PENS Outage Index. Second is reliability given by PRI, the PENS Reliability Index. Third, is stability, PSI, the PENS Stability Index. Finally, fourth is quality, PQI, the PENS Quality Index. Together, these four form the components that cover the most important aspects from a time series of data as their respective names indicate. All the components use voltage measurements to calculate their value.

With respect to reliability and quality, from reference [[1]]

Reliability has sometimes been classified as "how quality changes over time." The difference between quality and reliability is that quality shows how well an object performs its proper function, while reliability shows how well this object maintains its original level of quality over time, through various conditions.

More specifically from the same source,

- *Quality = Does the object perform its intended function? If so, how well does it perform its intended function?*
- *Reliability = To what level has said object maintained this level of quality over time?*

So PQI measures the power provider's or distribution system's ability to provide the contracted voltage, while PRI measures how well that voltage is maintained within tolerance limits. However, PRI has an additional dimension from the above definition, which is the confidence level of its value which is explained in more detail below.

In addition to quality and reliability, stability is also included, defined as the degree to which the data is fluctuating from its reference value. Considered together, reliability, stability, and quality provide a comprehensive means of assessing the state of a sensor's voltage measurement or group of sensors' voltage measurements over a time period.

[1] https://asq.org/quality-resources/reliability, accessed 2022-02-25

Key to all these measurements is a reference voltage for each sensor. The reference voltage is updated weekly using a trailing historical sample from each sensor. This provides a way of tracking drifts in the sensor as well as in the distribution grid itself. Variations from the reference voltage are what drives the values of PENS-ORSQ.

1.1 Outage

O: outage refers to the case where the voltage being measured is zero, either directly via a voltage measurement or inferred by a dead backup battery. Either case indicates that no line voltage is being supplied. Additionally, there is a requirement that at least two proximate sensors have zero voltage for the “event” to be considered as a qualified power outage event. The purpose of this additional constraint is to avoid the possibility of counting singleton outages that may be due to sensor issues such as maintenance or equipment failure. Requiring at least two sensors in a power outage event is a more conservative estimate of outages less prone to false positives at the expense of more false negatives. Note, there are many valid single sensor power outage events such as a car accident knocking down a pole or an isolated transformer failure. However, Gridmetrics has explicitly taken a more conservative stance with respect to data interpretation. POI is defined as 1 minus the outage time divided by the time period being sampled.

1.2 Reliability

R: reliability, a measure of "efficiency" of being within a non-damaging tolerance of a reference voltage. PRI (PENS Reliability Index) is defined as the probability, with confidence, that the readings are within tolerance. PRI is defined as the product of two Beta probability distributions, one for under-voltage and one for over-voltage. Under- and over-voltages are defined with respect to a reference voltage for each sensor and are ±6% from that reference. This tolerance was selected based on examination of historical voltage data, as well as the ANSI C84.1 of ±5% standard plus 1% for the sensor resolution.

One of the key features of PRI is that it includes a user-defined confidence level. This considers that there are a finite number of measurements, meaning that given a confidence level, with more measurements, the yield is a higher PRI—i.e., there is a higher probability that what is being measured is a true representation when there are more measurements. In our case the confidence level is 95%, or significance level of 5%.

1.3 Stability

S: stability, a measure of the fluctuations in the voltages. Standard deviation is a common measure of fluctuations from a series of measurements. PSI (PENS Stability Index) is defined as 1 minus the standard deviation of V/V_{ref} (measured voltage over reference voltage) over a trailing historical time period. In some cases of many outages mixed with nominal voltages PSI can be negative. In these cases, PSI is set to zero to prevent any negative numbers.

1.4 Quality

Q: quality, a measure of deviation from reference. PQI (PENS Quality Index) is defined as a function that is close to 1 near the reference voltage but drops off rapidly as the voltage deviates from that value. Like the other measures, PQI is in the interval [0, 1] and close to 1 when the voltage is near nominal.

Specifically, PQI is comprised of the sum of two hazard functions, one for under-voltages and one for over-voltages. Combining the under- and over-voltages forms a comprehensive measure of power quality. The following are desiderata for a power quality index:

1. Bounded in range – makes comparisons and averaging simpler
2. Small changes near nominal values – don’t worry about slight deviations from normal fluctuations
3. Non-linear – emphasize larger changes
4. Saturates for lower or higher values – at some point the equipment is non-functional or damaged and can’t get worse beyond this level.

All these desiderata are satisfied by our choice of PQI as shown in Fig. 1.

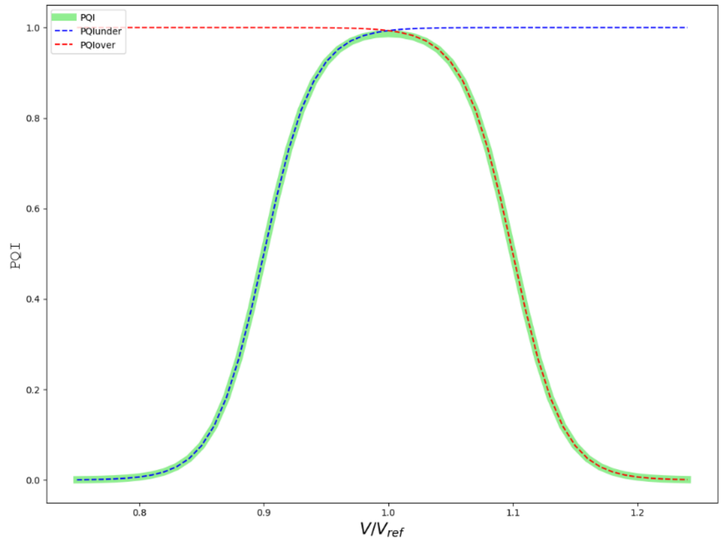

Fig. 1 PQI in terms of V/V_{ref}.

1.5 Index Condition Levels

In the GridCON report POI, PRI, PSI, and PQI values are converted to integers between 1 and 5, corresponding to different severity conditions as shown in Table 1. The conversion from raw values to the different condition levels are currently determined from historical data using the year 2021 as the reference.

Table 1. POI, PRI, PSI, PQI Condition Definitions

Condition Level	Condition Level
5	Standard
4	Slight
3	Strained
2	Significant
1	Severe

There are three steps involved in going from the raw distribution of index values to the condition level.

1) Set index threshold levels for each index. The thresholds correspond to probabilities that the index will be above, below, or in a range of threshold values. The threshold values were chosen to intuitively correspond to the severity level. The actual threshold values used for PRI, PSI, and PQI are shown in Table 2 and in Table 3 for POI.

2) Given the distribution of values from a particular region and time period, calculate the probability that the index is less than the thresholds in 1). If the probability exceeds the thresholds set in 1) set the condition level accordingly. The actual values for the condition levels for the indexes is shown in Table 2. As an example, 7/8^{ths} of the time the indexes will be at the “Standard” level and about 1.56% of the time they will be in the severe condition. In general, these thresholds can be adjusted for each index.

Table 2. PRI, PSI, PQI (P*I) levels

Condition Level	Probability of Index at Index Threshold
5	(1/8) 0.125 $\leq$ P*I
4	(1/16) 0.0625 $\leq$ P*I < 0.125
3	(1/32) 0.03125 $\leq$ P*I < 0.0625
2	(1/64) 0.015625 < P*I < 0.03125
1	P*I $\leq$ 0.015625

POI values are set with different thresholds. Again, these can be adjusted for particular scenarios. For example, a particular customer may want tighter (higher percentiles) thresholds for the purpose of more quickly responding to a deteriorating situation. On the other hand, looser (lower percentiles) thresholds will trigger fewer alarms and only require attention in much more dire situations. Also, the thresholds in Tables 2 and 3 are from the 2021 for the entire Gridmetrics footprint of around 300,000 sensors. In some cases, for example, if a particular state wanted to track its counties the more appropriate thresholds would be with respect to that state's historical record rather than the entire U.S. Thus, in addition to tailoring a report to a particular region like a state, the percentiles can also be changed as mentioned above.

Table 3. POI levels

Condition Level	Probability of Index at Index Threshold
5	0.015 $\leq$ POI
4	0.010 $\leq$ POI < 0.015
3	0.0075 $\leq$ POI < 0.010
2	0.0005 $\leq$ POI < 0.0055
1	POI < 0.005

Fig. 2 shows relationship between index values (0-1) and index conditions (1-5) for P[ORSQ]I. Note, the distributions in the figure are for each sensor for a year corresponding to about 80 million data points. In the GridCON report the values are the average from all the sensors for that day in a particular region which is not a direct correspondence to the underlying distributions used to determine the condition level. The direct comparison would be to use similarly averaged data from the historical period, but as there are only 365 data points, the tails are very sparse which would lead to a high uncertainty in the condition level. Over time as more data is accumulated the direct comparison to the historical data becomes feasible. Therefore, given the historical daily data limitation, the best choice for determining the condition level is to use the full spectrum of data, as has been done.

The "comb-like" structure in POI is due to the finite sampling rate (in this case every 5 minutes, with some jitter) which creates a more discretized distribution. Note the log scale on the vertical axis which highlights the most striking feature of these plots which is how tightly peaked they are—a tribute to how well the grid usually operates. In particular, note how quickly the distributions tail off from their peak while spanning four orders of magnitude for the range shown.

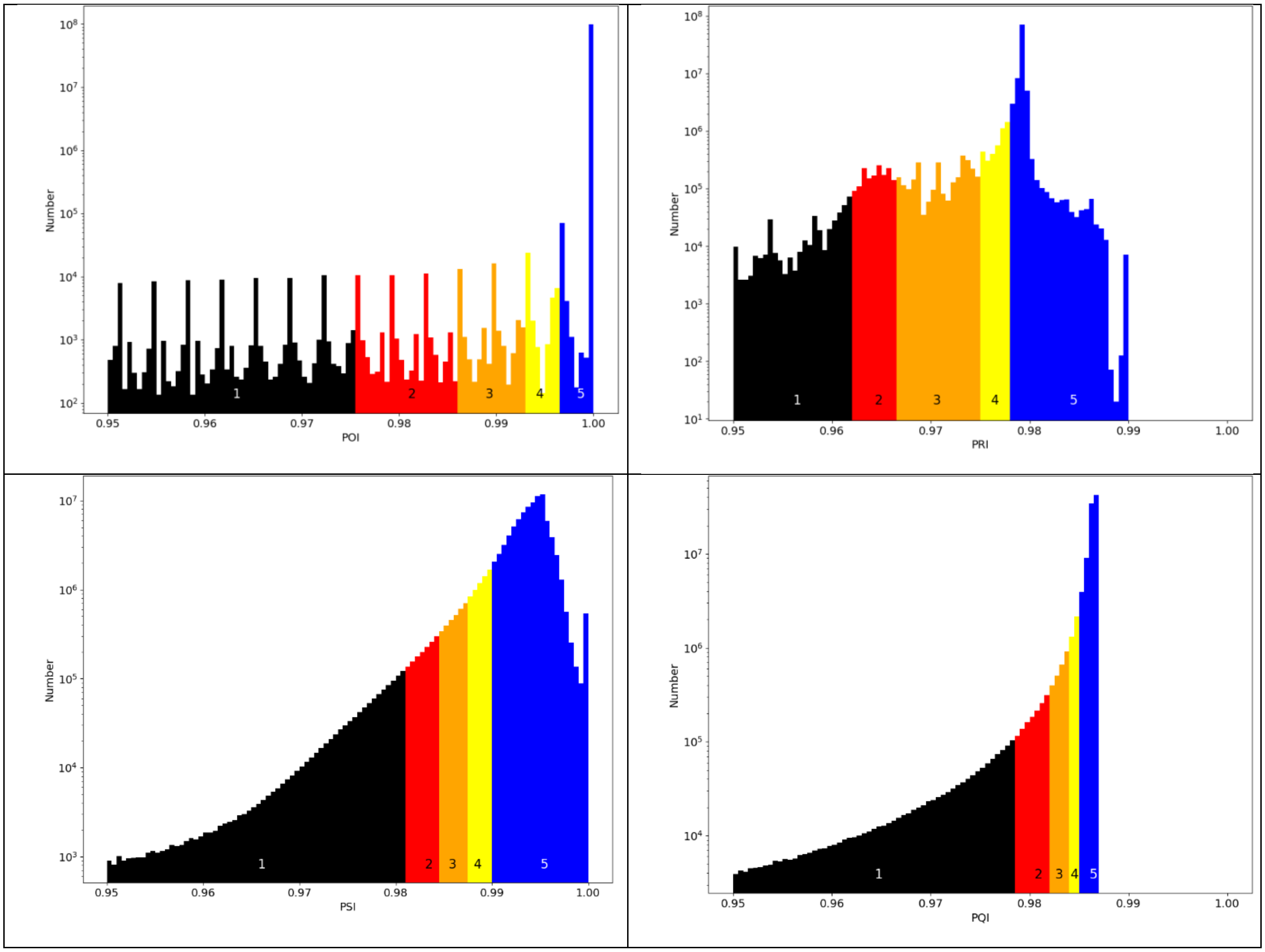

Fig. 2 PRI actual distribution for 2021 showing the relationship between the PRI value (0-1) and the PRI condition (1-5).

1.6 PGI: GridCON Report Levels

GridCON stands for Grid CONdition level and is inspired by U.S. military Joint Chiefs of Staff DEFCON for DEFense CONdition. Specifically, GridCON is based on the value of PENS-ORSQ. These four: POI, PRI, PSI, and PQI characterize the important features of a times series of voltage measurements. Under "standard" conditions all four will be ~1. The value of PGI is constructed from the average of POI, PRI, PSI, and PQI so that:

$$PGI = round((POI + PRI + PSI + PQI) / 4 - .01)$$

Under normal conditions all four of PGI's components will be 5 so that PGI will also be near 5 and the rounding is upward. The -.01 is a "tie-breaker" in the case of a mantissa of 0.5 so that PGI will be rounded down—a more conservative approach. Although the outage, reliability, stability, and quality are somewhat correlated, their average nevertheless provides an important measure of the overall performance of what is being measured.

A flowchart of the GridCON calculations is shown in the figure below. The default time period is one day. The step-by-step the process is:

1) voltage times series data from all sensors

2) calculate POI, PRI, PSI, PQI using data from step 1) and voltage reference data

3) find the POI, PRI, PSI, and PQI corresponding to their respective thresholds

4) average these values together to obtain GridCON (rounding down if the mantissa = 0.5)

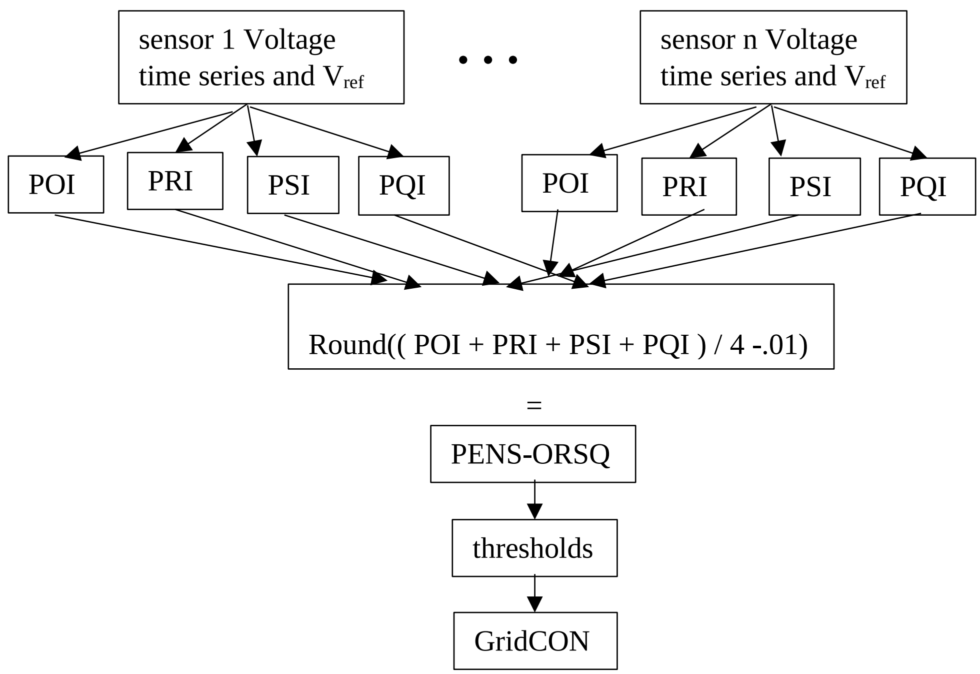

Fig. 3 PENS-ORSQ and GridCON flowchart.

Appendix 1: Outage
The outage for a sensor is calculated as:

$$POI = 1 - \frac{\sum_{outages} outage\_time - \sum_{battery\ out} dead\_battery\_time}{total\_sample\_time}$$

Thus, POI the fraction of time that a sensor is not in an outage or has a dead backup battery (which is very likely due to a power outage). The *total_sample_time* is currently set to one day.

Appendix 2: Reliability
The Beta distribution measures efficiency, and in this case, the "efficiency" is the probability that a voltage measurement will be under- or over-voltage. The assumption made here is that the voltage conformance within pre-set limits is given by a Bernoulli random variable. The voltage is in conformance (a success if above the lower threshold or below the upper threshold depending on the test) with probability p, where p is calculated over a pre-defined historical period. The user defines a confidence-level 1-α that is used to give the confidence interval for a given upper and lower bound. Because of the aforementioned non-Gaussian issues with the data the Clopper-Pearson score intervals are used given by:

$$p^{upper} = B(1 - \alpha, m + 1, n - m) \qquad (1)$$

$$p_{lower} = B(\alpha, m, n - m + 1) \qquad (2)$$

where n is the number of historical measurements and m is the number of conforming measurements and B is the Beta function whose probability density function is defined as

$$B(\alpha, a, b) = \frac{\Gamma(a+b)\alpha^{a-1}(1-\alpha)^{b-1}}{\Gamma(a)\Gamma(b)} \qquad (3)$$

and Γ is the gamma function defined as:

$$\Gamma(z) = \int_0^{\infty} x^{z-1} e^{-x} dx. \qquad (4)$$

The motivation for using the Beta function is that in Bayesian inference it represents the conjugate prior probability distribution for the voltages. The definition of "conforming measurements" is $V/V_{ref} > 0.94$ for p_{lower} and $V/V_{ref} < 1.06$ for p^{upper}. In the end, PRI is defined as the product:

$$PRI = p_{lower} p^{upper}$$

In application to ORSQ the value of PRI is calculated daily for each sensor. For custom reporting different time periods can be selected and aggregation of sensors can also be used.

Appendix 3: Stability
In theory stdev(V/V_{ref}) could be greater than 1 so that PSI could be negative but that is a pathological case where $V \gg V_{ref}$, likely due to bad measurements from the sensor. Any real readings $>2V_{ref}$ would damage or destroy equipment. Thus, under typical scenarios PSI will mostly be close to 1 because stdev(V/V_{ref}) ~ 0.01 so that PSI =

1 - stdev(V/V_{ref}) ~ 1. This makes PSI consistent with PRI and PQI in that nominal values are close to 1. Any values of PSI < 0 are set to 0.

Appendix 4: Quality

Hazard functions are related to failure rates and provide a good starting point for defining PQI. Sigmoid functions are one popular choice for hazard functions and have all the desiderata described above. The sigmoid function is used in our definitions of PQI. Specifically, PQI_{under}, PQI_{over}, and PQI define the power quality with respect to under-voltages, over-voltages, and any voltage, respectively.

$$PQI_{under} = \frac{1}{1 + exp(-\beta_{under}(V/V_{ref} - V_{off\_under}))}$$

$$PQI_{over} = \frac{1}{1 + exp(-\beta_{over}(-V/V_{ref} + V_{off\_over}))}$$

$$PQI = PQI_{under} + PQI_{over} - 1$$

where β is a rate factor that in general will be different for under- and over-voltages because of the different damage profiles resulting from under- and over-voltages. Namely, over-voltages are more likely to damage or destroy equipment rather than making it inefficient as may be the case for some under-voltage scenarios. V_{off} is an offset that defines the half-height of PQI.

The specific values for the β's and V_{off} offsets were chosen so that at ±10% from $V = V_{ref}$ the value of PQI ≈ 0.5 and ±20% PQI ≈ 0.995. In particular, $\beta_{under} = \beta_{over} = 50$, $V_{off\_under} = 0.90$, $V_{off\_over} = 1.1$. These are the values that went into Fig. 1.

Unlike POI, PRI and PSI, PQI can be calculated point-by-point and does not need a history. However, in GridCON the default time period is to look at a one-day period, so PQI is averaged over this period on a sensor by sensor basis.

Appendix 5: GridCON

A.5.1 Structure of the GridCON Daily Report

GridCON for FEMA regions and over the U.S. is given by the Gridmetrics' Daily Domestic Power Intelligence Report. An example of which is shown below in Figure 3. Table 4 explains in detail what goes into the various fields of the report. All references to geographic regions are with respect to Gridmetrics' coverage area. Potential population impacts are based on Landscan daytime populations[2]. Outage, Reliability, Stability, Quality, and GridCON are color-coded by value to easily identify troublesome regions and performance.

In the GridCON report, the bottom row has the U.S. national values for outage, reliability, stability, and quality. The values in the final row are calculated using the same thresholds as for the regions, but for the entire US set of Gridmetrics sensors, rather than some average of the individual regions. The same is true for the GridCON value in the lower right.

[2] https://landscan.ornl.gov

Table 4. Gridmetrics Daily Domestic Power Intelligence Report

Row or Column	Explanation
Row 1	Headers
Row 2	Sub-headers
Rows 3-12	Stats for each Region
Column 2	Potential population impacted by outages
Column 3	Approximate percent of population covered by Gridmetrics sensors as represented by being within 1km of a Gridmetrics sensor
Column 4	Number of outages
Column 5	Percent USNG cells with an outage
Column 6	POI – PENS Outage Index
Column 7	PRI – PENS Reliability Index
Column 8	PSI – PENS Stability Index
Column 9	PQI – PENS Quality Index
Final Row	U.S. National values
Row 1, Final Column	Current GridCON of the U.S. -- a quick way to see the state-of-the-grid
Row 13, Column 3	Percent population covered is calculated from all the regions combined
Row 13, Columns 5-9	Average of each region’s value, i.e., each region is equal-weighted Senatorial-style so that lesser populated regions are not under-represented; the average of the region’s ORSQ was used in the calculation of the U.S. GridCON
Final Row, Left	7-day history of GridCON for each region and the U.S
Final Row, Right	Current day’s PENS outage map

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Gridmetrics PENS

Power Event Notification System

USNG = US National Grid 1km x 1km cell

Outage event: involves at least two Gridmetrics sensors in the same or adjacent USNG cells

Aggregated measurements collected from 300,000+ power sensors every 5 minutes

Gridmetrics PENS-ORSQ

Outage Index: 1 minus the fraction of sensors with power outage

Reliability Index: derived from probability with confidence that sensors are within +6% of reference voltage

Stability Index: 1 minus the standard deviation from reference voltage

Quality Index: measure of deviation from reference voltage

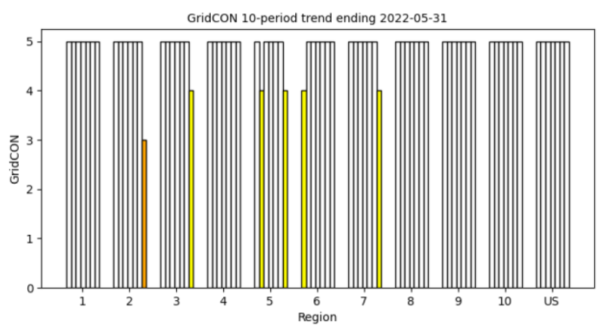
O, R, S, Q calculated for this day's data and compared to historical national values

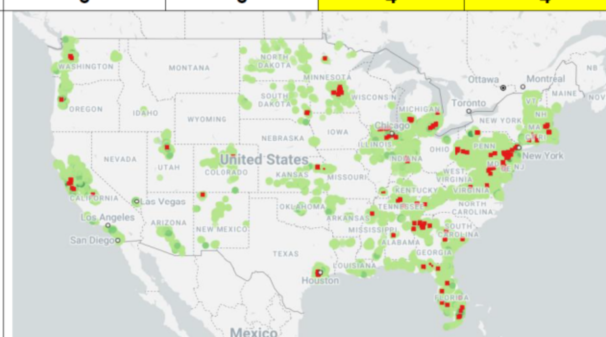
Daily GridCON Report for 2022-05-31

4

1 = Severe
2 = Significant
3 = Strained
4 = Slight
5 = Standard

Region	Approx % Population Covered	% USNGs with Outages	Number of Outages	Potential Population Impacted	Outages	Reliability	Stability	Quality	GridCON
1: CT MA ME NH RI VT	74.4	0.4	232	43,473	5	5	5	5	**5**
2: NJ NY	18.7	0.4	149	55,999	5	2	3	1	**3**
3: DC DE MD PA VA WV	78.7	0.6	791	276,760	4	4	5	4	**4**
4: AL FL GA KY MS NC SC TN	39.0	0.5	972	113,628	5	5	5	5	**5**
5: IL IN MI MN OH WI	46.7	0.8	740	164,481	4	5	5	1	**4**
6: AR LA NM OK TX	31.2	0.4	506	96,827	5	5	5	5	**5**
7: IA KS MO NE	17.8	0.7	34	4,036	4	5	5	1	**4**
8: CO MT ND SD UT WY	67.7	0.5	198	58,891	5	5	5	5	**5**
9: AZ CA HI NV	49.1	0.3	280	143,645	5	5	5	5	**5**
10: AK ID OR WA	61.6	0.2	64	42,200	5	5	5	5	**5**
Combined Coverage	**45.4**	**0.5**	**3,966**	**999,940**	**5**	**5**	**5**	**4**	**4**





Click here for the day's outage PENS-Playback.

Fig. 3 Sample of Gridmetrics' Daily Domestic Power Intelligence Report.

A.5.2 Guidelines for interpreting the GridCON Daily Report

Referring back to Fig. 3 we can see that on this particular day (not a typical one) there were a wide range of index values even across the same region. The different index values for FEMA region 2 tell a story about what happened that day and highlight the unique value that these four indexes have in understanding the grid within a particular region. For example, from an outage perspective (POI = 5) this day was fine. However, from a quality perspective (PQI = 1) this was a very bad day, meaning that the voltages for the region were far off their reference values. The reliability (PRI=2) means that not only were the values off their reference values, many measurements were also outside the tolerance window. Finally, the voltages were not that stable (PSI = 3) meaning that not only were the voltages off their reference, but they were also fluctuating significantly. Altogether, these index values for FEMA region 2 on this day point to a grid that was significantly off its reference voltage and with a wide variation in voltages, but with very few outages. This was a day of bad regulation, not outright outages. As the GridCON for that day (= 3), the grid was "strained."

Table 5 shows some hypothetical P[ORSQ]I values and their interpretation. These cases show the power of the four-dimensions of the PENS GridCON indexes in their ability to identify many different grid scenarios as well as their magnitude. In totality there are 625 possible permutations and 625 stories to go along with them. Four are shown here as examples to give an idea of the richness of meaning embodied by the PENS Outage, Reliability, Stability, and Quality condition levels.

Table 4. Interpretation of Possible PENS Index Condition Level Values

Outage	Reliability	Stability	Quality	GridCON	Interpretation
5	2	3	1	3	Few outages, large voltage deviations
2	5	5	5	4	Many outages, but nominal otherwise
5	2	5	2	3	Few outages, voltages are stable but systematically out of tolerance
5	5	5	3	4	Few outages, voltages within tolerance, stable, but noticeably off of reference