Key Performance Indicators for Energy Systems

nLine Inc, prepared June 2023

This document introduces the key performance indicators (KPIs)[1] provided by nLine to evaluate and quantify the performance of an energy supply, whether that be a national grid network or a local mini or microgrid system. The KPIs are summarized in the following table and discussed in detail in the following pages, with each KPI accompanied by a *KPI statement* to provide a concrete example of the definition and suggestions for improving the KPI.

[1] A KPI is defined over a certain customer set and time period. For example, we could obtain a KPI for all grid-connected customers in Accra, Ghana in a given year or for customers supplied by a particular microgrid in a given month.

KPI Name	Definition	Type
System Average Interruption Duration Index (SAIDI)	Average cumulative outage time experienced by a customer *[hours]*	Reliability
System Average Interruption Frequency Index (SAIFI)	Average number of outages experienced by a customer *[number of interruptions]*	Reliability
Average Voltage	Average voltage delivered to customer *[Vrms]*	Quality
Hours Undervoltage	Average time customer experiences very low voltage *[hours]*	Quality
Minutes Overvoltage	Average time customer experiences very high voltage *[minutes]*	Quality
Average Frequency	Average synchronous grid frequency *[Hz]*	Quality

Table 1: Summary of nLine's Power Quality & Reliability KPIs

nLine recognizes that standard KPIs for evaluating an energy supply can be insufficient to evaluate the full impacts of supply performance. For instance, average system performance does not capture the range and equality of customer experience, and power quality metrics do not quantify the domain-specific impacts of those KPIs on critical infrastructure. nLine provides and advocates for transformations of these KPIs to meet this need, and several are listed at the end of this document.

Power Reliability KPIs

Reliability KPIs quantify how often electricity is *off* for customers. They are widely used by electric utilities and regulators and defined in IEEE Standard 1366.

System Average Interruption Duration Index (SAIDI) is the average total outage time experienced by a customer over a period. Exactly calculating SAIDI requires the total outage time experienced by *each* customer, which is usually unknown. Instead, nLine uses statistical approaches to estimate SAIDI from a representative sample of customer experiences[2]. In off-grid systems, SAIDI may be expressed as a system "uptime" metric.

In April 2022, customers in the Achimota district of Accra, Ghana experienced an average SAIDI of 19 hours over the course of the month.

For N customers, SAIDI across time period T is defined as:

$$SAIDI(N,T) = \frac{\sum_{i=1}^{N} O_{i,T}}{N}$$

where $O_{i,T}$ is the total duration of outages experienced by customer i over the period T.

[2] blog.nline.io/estimating-saidi

TO IMPROVE SAIDI, the number and duration of outages must be reduced. Replacing aged grid equipment, trimming vegetation around lines that can cause faults, and ensuring adequate electricity supply to avoid load shedding all reduce outage numbers. Modern switching equipment and monitoring tools for fast identification, localization, and resolution of failures reduce outage durations. In solar microgrids, adequate sizing of panels, storage, and wiring will improve SAIDI.

System Average Interruption Frequency Index (SAIFI) is the average number of outages experienced by a customer over a chosen period. As with SAIDI, nLine estimates SAIFI from a representative sample. SAIFI alongside SAIDI gives a more holistic picture of outage experience. For example, frequent, short outages may be lost in SAIDI but highlighted in SAIFI, reflecting their high impact, especially in industrial or health facilities where short outages can interrupt manufacturing processes or medical care delivery, incurring significant cost and grave human consequences.

In November 2021, a minigrid-powered healthcare facility in the Democratic Republic of Congo experienced a SAIFI of 56 interruptions over the course of the month.

For N customers, SAIFI across time period T is defined as:

$$SAIFI(N,T) = \frac{\sum_{i=1}^{N} F_{i,T}}{N}$$

where $F_{i,T}$ is the number of outages experienced by customer i over T.

TO IMPROVE SAIFI, outages occurrences must be reduced. Ensuring equipment maintenance is timely, supply is adequate to avoid load-shedding, and infrastructure is shielded from weather impacts will reduce outage numbers. Proper protection system design (switches, fuses, etc.) avoids nuisance circuit trips and ensures the minimum set of customers' power is turned off for fault isolation or maintenance. In solar microgrids, adequate generation and storage, and proper fuse settings will improve SAIFI.

Power Quality KPIs

Power quality KPIs quantify the quality of electricity when it is *on*.

Voltage Quality KPIs

For electricity to be useful, the voltage at which it is delivered must be in a reasonable range. The ideal range depends on the type of load being supplied; however a widely accepted standard is to maintain voltage within ±10 % of nominal (generally 220-240 V on the African continent). Voltage outside this range can cause trips, overheating, damage and reduced lifespan for various equipment and appliances. EN 50160 and ANSI C84.1 are respectively the European and North American standards for supply voltage quality. nLine produces the following three KPIs to capture voltage quality.

Average Voltage
is the average voltage over time and across customers. It should be close to the nominal voltage.
In the week of July 4, 2022, customers in the Dansoman district of Accra experienced average voltage of 225 volts.

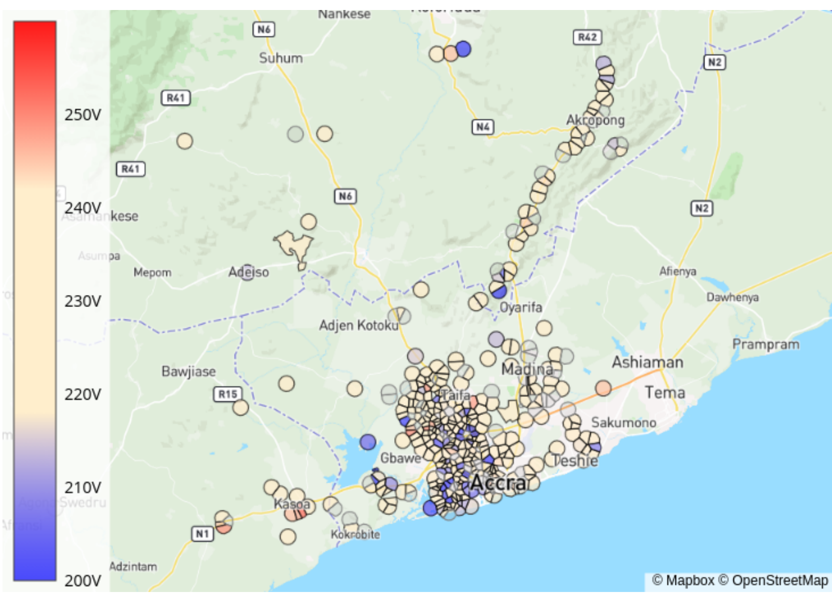

Figure 1: An nLine dashboard visualizing average voltage across the city of Accra, Ghana for a week in 2022.

Hours Undervoltage
is the total hours per chosen period that voltage is below 90% of nominal averaged across customers. Sustained undervoltage can damage consumer appliances, slow electric heating and cooking, and

degrade supply side electric infrastructure. Undervoltage is a common issue in low- and middle-income countries due to overloaded, undersized grid infrastructure.

On August 5, 2022, a minigrid powered health clinic in the Democratic Republic of Congo experienced 15 hours of undervoltage.

Minutes Overvoltage
is the total minutes per chosen period that voltage exceeds 110% of nominal average across customers. Significant overvoltage can damage equipment or cause trips. Overvoltages are less prevalent than undervoltages, especially in bulk grids.

On August 1, 2022, households powered by a microgrid experienced 5 minutes of overvoltage.

> TO IMPROVE VOLTAGE QUALITY, lines and equipment must be adequately sized to mitigate overloading and excessive voltage drop. Regulation equipment, such as capacitor banks or voltage regulators, can reduce voltage line drops. In solar microgrids, a performant inverter and well-sized battery are key to voltage quality.

Frequency Quality KPIs

In bulk grids, system frequency indicates the aggregate balance of demand and supply. Frequency must be tightly controlled around nominal (50 Hz) to avoid instability, generator damage, and impacts on sensitive loads. In many large grids, frequency is maintained within $\pm$ 0.5% of nominal. In microgrids, frequency depends on generator or inverter control, and should ideally remain within $\pm$ 5% of nominal to avoid damage to motors and sensitive loads (see IEEE Standard 1547). nLine produces the following KPI to capture grid frequency quality.

Average Frequency
is the average system frequency, the single frequency experienced by all customers supplied by a common grid, over time.

On January 1, 2022, average frequency in Ghana was 50.14 Hz.

> TO IMPROVE FREQUENCY STABILITY in bulk grids, aggregate energy balance must be carefully and continually controlled. This is the purview of the highest level of grid control, involving generators, power purchases, and markets. In microgrids, ensuring inverters and generators are sized correctly and have functioning controllers will improve frequency stability.

Derived Performance Indicators

Power quality and reliability KPIs can be transformed to better capture the lived experience of an energy system. These indicators can capture the range and equality of a metric to report on the diversity of customer experiences or they can capture the impact of power quality and reliability on specific critical infrastructure. nLine captures many derived performanced indicators for specific applications. We provide two examples below.

Gini Index
is the equality of a KPI. A higher Gini index would indicate that a metric is less equally distributed across the measured individuals or groups. For instance one neighborhood having good average voltage and another having very poor average voltage would lead to a higher Gini index for the average voltage KPI. The Gini index can also be used to compare relative equality between populations.
In 2020, residents of the Achimota district of Accra experienced a voltage inequality of 0.45, similar to Ghana's income inequality (0.43)

The Gini index is defined from 0 to 1, with 1 being the most unequal. It is defined as:

$$G = \frac{\sum_{i=1}^{N} \sum_{j=1}^{N} |x_i - x_j|}{2n^2 \bar{x}}$$

where x_i is the performance of an energy system for group or individual i and there are n groups.

> TO IMPROVE GINI INDEX, improvements should be targeted at individuals, subgroups, or neighborhoods currently experiencing the worst power reliability or quality.

Equipment Performance
is a quantification of how power reliability and quality impacts specific equipment based on its requirements. This captures both reduced efficacy and likelihood of breakage.
In the week of May 23, 2023, a grid-powered health clinic in Sierra Leone never had sufficient voltage to power a computer despite having power for nearly 12 hours per day.

> TO IMPROVE EQUIPMENT PERFORMANCE local voltage stabilizers or transformers may be added or the power quality of the energy source can be improved.