Overvoltage Challenges in Low-Resource Settings

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EXECUTIVE SUMMARY

Purpose

Following the 2019 publication[1] of power quality analysis by New Horizons and country collaborators, updated data and analysis indicate widespread overvoltage events, which has important safety implications for cold chain equipment specification and design.

The objective of this document is to provide an overview of the prevalence and severity of these observed extreme overvoltage events, to help inform any needed updates to performance specifications or procurement requirements.

Contributing Data and Analysis

- Voltage data were collected in 347 health facilities in both Kenya (226 units) and Nigeria (121 units) [2].
- Data collection was conducted from March 9, 2018 through March 31, 2021, with an average of 2.3 years of data per facility.
- We evaluated the maximum voltage levels experienced at each location, as well as the number and duration of all measured 'extreme overvoltage' events where mains voltage exceeded 350 V (an approximate level that can damage equipment).

Results and Conclusions

- PQS-prequalified cold chain equipment (CCE) may be inadequately protected against extreme voltage levels experienced in real-world settings:
  - 8% of locations experienced voltages that exceeded the PQS-required protection level for voltage stabilizers (415 V).
  - 18% of facilities experienced voltages over 350 V that could damage unprotected equipment.
  - The highest observed voltage event across all locations was 507 V.
  - These events were experienced in the average 2.3-year period of data per facility; additional sites will likely experience similar potentially damaging events within the expected 10-year CCE lifetime.
- **All CCE connected to AC power in low-resource environments should include a voltage stabilizer or other voltage protection device designed to properly protect CCE from the voltage levels observed here.**
- **We recommend that PQS increase the required voltage protection level for voltage stabilizers, as well as making device designers/suppliers aware of these observed voltage levels so that they can design products accordingly.**

[1] *Power Quality Challenges in Low-Resource Settings*, Roderick Hinman *et al*., white paper from Global Good Fund 1, LLC, 2019. Available at http://power.2to8.cc, April, 2021.

[2] Data collected by Aucma CFD-50 vaccine refrigerators. An overview of the CFD-50 voltage monitoring system behavior is available on page 13 of *Power Quality Challenges in Low-Resource Settings.*

NEW HORIZONS

INTRODUCTION

New Horizons and country collaborators published a detailed power quality analysis in 2019

- The 2019 analysis focused on providing an overview of power availability and quality measured in health facilities in both Kenya and Nigeria, and the summary conclusions were that:
  - Reported voltages deviated significantly from nominal, so voltage stabilization can improve equipment availability.
  - Most health facilities experience power interruptions, and they are common events.
  - Extreme voltage conditions can pose a risk of permanently damaging medical equipment.
- The vaccine refrigerators that were used to collect the dataset for the 2019 analysis have continued to collect power data, and New Horizons has continued to evaluate the voltage data from these units. **From these updated data and analysis, extreme voltage conditions have continued to occur, and we believe the results have important implications for specifications and equipment design.**

WHO PQS voltage stabilizer specifications[1] mandate the performance requirements for both standalone and integrated voltage stabilizers that are purchased for use with Cold Chain Equipment.

- Gavi CCEOP-funded procurements require that all mains-powered CCE be supplied with a voltage stabilizer, for both the protection of CCE and to improve operation in variable voltage environments.
- The currently active WHO PQS voltage stabilizer specification VS01.5, based on the best data available at the time of publication (March 2018), requires that stabilizers power downstream equipment at input voltages up to 278 V, and withstand a continuous input voltage of 415 V.
- Based on the updated extreme-overvoltage data from this analysis, we believe there is justification to increase the 'voltage withstand' threshold in VS01.5 from 415 V to a higher level, so that mains-connected CCE utilizing a PQS voltage stabilizer are better protected from potentially damaging voltage conditions.

[1] PQS/E007/VS01.5, Single phase voltage stabilizer for ac powered refrigerators and freezers, 2018.

- E007 category documents: https://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/catdocumentation.aspx?id_cat=36
- direct link: https://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/LinkPDF.aspx?UniqueID=5ec02fae-c969-4626-b17e-09705949239b&TipoDoc=PQS_x0020_Document_x0020_Type&GuidDoc=14fc8bcc-d610-4e0c-a690-b5fcbf09dab6

CONTRIBUTING DATA AND ANALYSIS METHODS

Contributing Data

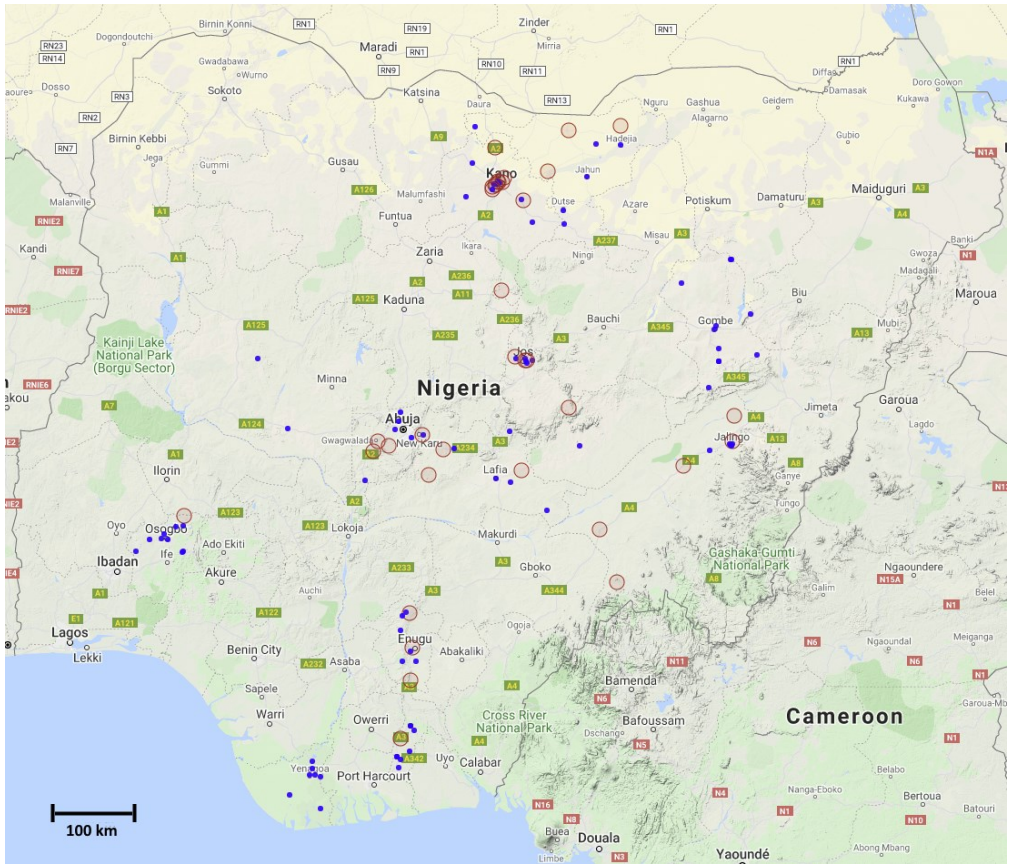
- Voltage data were collected by CCE in 347 health facilities in both Kenya (226 units) and Nigeria (121 units). The CCE contains an integrated monitoring system so that an external monitor does not impact performance of the equipment. Its battery maintains operation up to 14 days without usable input power and can withstand up to 700 VAC so that data on both good and poor power conditions may be collected.
- 293,654 facility-days of voltage data were analyzed; an average of 2.3 years of data per facility.
- Data collection was conducted from March 9, 2018 through March 31, 2021.
- In 6 instances, CCE were moved between facilities, so we focus on locations rather than devices.
- Across all facilities, the proportion of time with reported voltage data is 93.9%. Data outages include periods where power interruptions exceeded the monitoring system's battery capacity.

Analysis

- We used these voltage levels:
  - 350 V is approximately the value that could damage equipment designed for 230 V–240 V systems (depending on individual equipment details).
  - 415 V is the present withstand threshold in the PQS VS01.5 voltage stabilizer specification.
- We analyzed:
  - Maximum voltage experienced at each location
  - Overvoltage events, where an "event" starts when the voltage rises above 350 V and lasts until it returns below 350 V.
- We have focused on reporting maximum voltages experienced, even if that voltage was only reported for a single 10-second averaged sample, because 10 seconds can be a 'long' time for some electrical designs and components.
  - See slide 7 for further detail on durations of overvoltage events.
- As this analysis considers the highest voltage recorded at each location, it is important to note that the voltage samples collected on a 10-second interval are not 'instantaneous samples' but rather represent an average of 10,000 raw sample values collected over that period.
  - This means that each voltage sample used for the purpose of this analysis will tend to under-report actual peak voltages that may have occurred for shorter than the 10-second sampling period.
  - Furthermore, single spurious raw voltage samples will not significantly affect the outcome as they will be averaged with many others.

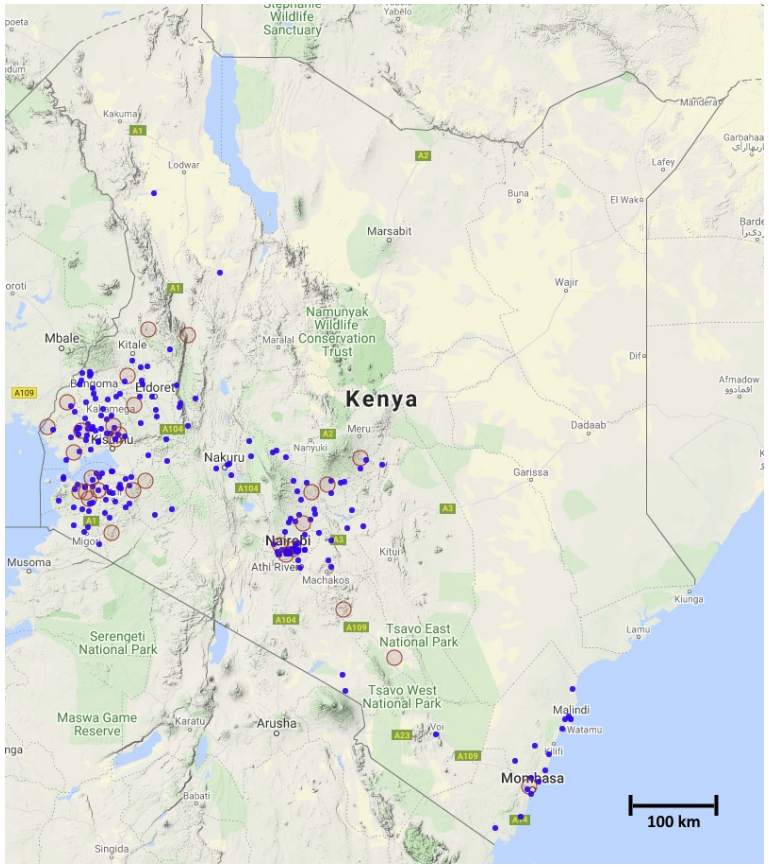
FACILITY LOCATIONS

Nigeria



Locations of 121 facilities in the FCT and eleven states in Nigeria where power data were collected.

Kenya



Locations of 226 facilities in 36 counties in Kenya where power data were collected.

- **Blue dots are facilities that did not experience input voltages exceeding 350 V during the time period of this analysis.**
- **Red circles are facilities that experienced input voltage ≥ 350 V. Note that they occur in urban and rural areas alike.**

PEAK OVERVOLTAGE SUMMARY

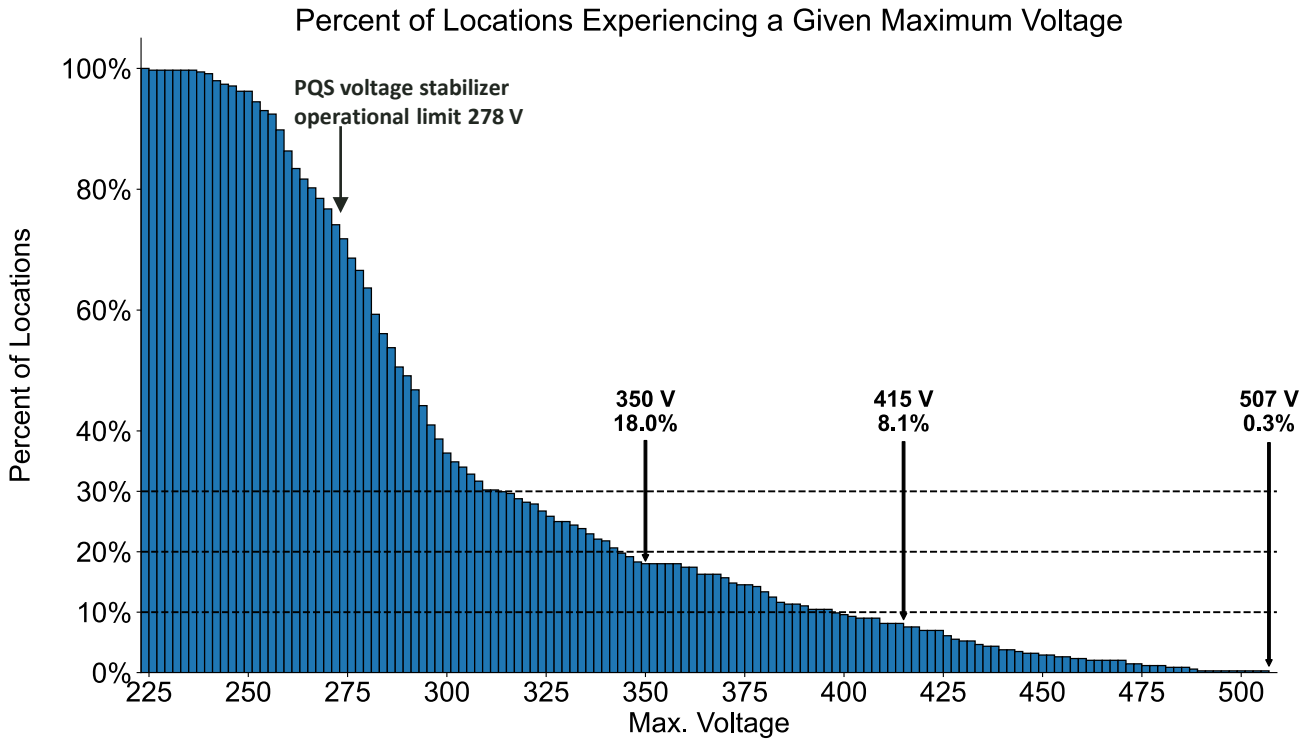
Here we have analyzed the peak voltage experienced at each location, and this chart reports what portion of facilities have experienced a voltage level of at least a given value.

- For example, 100% of locations have experienced at least 225 V, which is an expected result, given that nominal mains voltage is 230-240 V.

Important results from this analysis are:

- 18% of locations experienced a voltage level of at least 350 V, **confirming that voltage protection is critical for mains-connected device survival.**
  - This includes 29 locations in Kenya and 35 locations in Nigeria
- 8% of locations experienced a voltage level of at least 415 V, the present PQS stabilizer test 'withstand' level. **This level may need to be raised based on these field data.**
- **A facility experienced a voltage of 507 V – this is the peak 10-second average voltage from this dataset.**

It is particularly notable that the overvoltage conditions experienced at these facilities were observed **within the average ~2.3-year period of data collection. As time progresses, additional facilities are expected to experience dangerous overvoltage conditions, so these percentages will rise over time.**

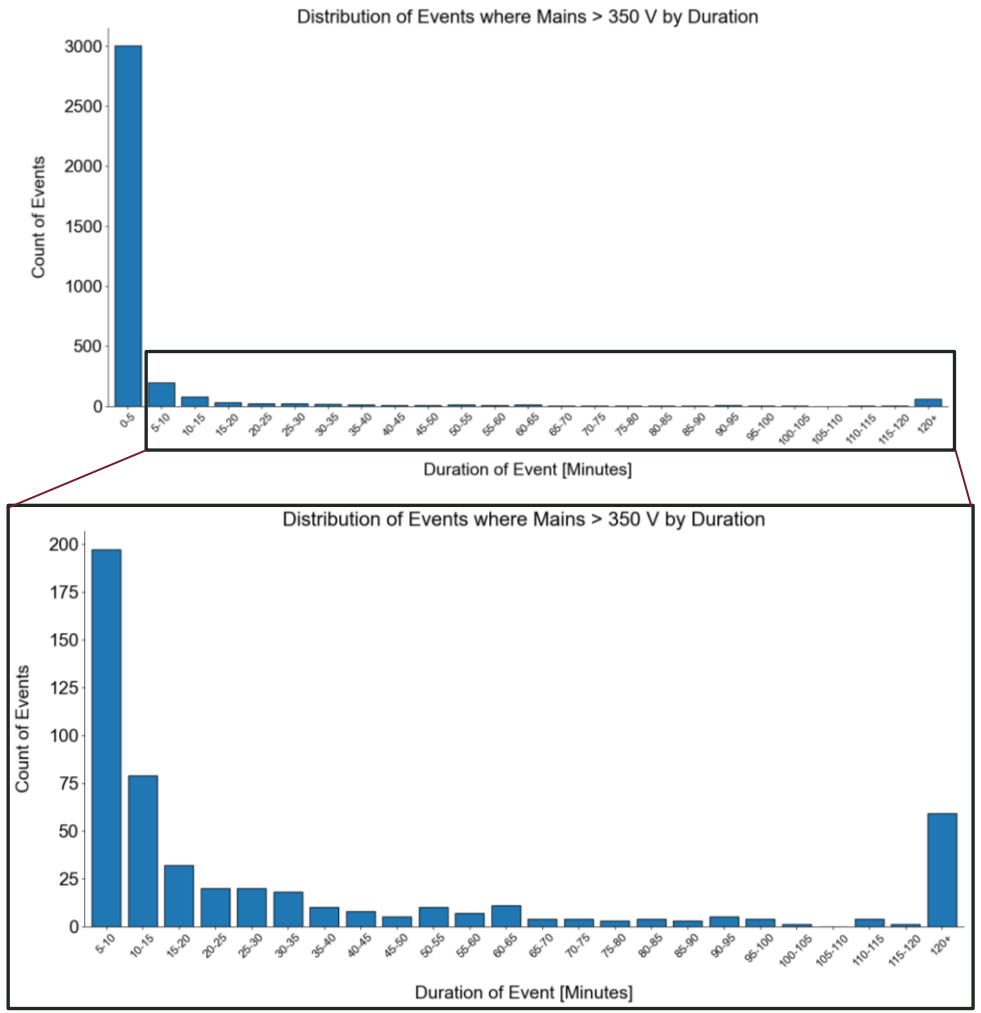


Voltage data from 347 health facilities in Nigeria and Kenya show 8% of locations experienced a voltage event of 415 V or higher, with one device experiencing > 500 V, pointing to the need for robust protection

OVERVOLTAGE EVENTS BY DURATION

These plots show all the events where the voltage was above 350 V, categorized by how long they lasted. The lower plot is the same data as the upper plot, with the 0-5-minute bar excluded to show the detail of longer duration events[1] .

- **Overall, there were 3511 events across all 64 locations where voltage exceeded 350 V.**
- **60 events (1.7%) of events were longer than 120 minutes (2 hours), and the longest lasted for 15 hours[2]. For reference, two hours is the duration of the voltage withstand test within the PQS voltage stabilizer test protocol; this duration should be sufficient to identify most equipment failure modes.**



While many overvoltage events are less than 5 minutes in duration, it is not uncommon for overvoltage events to last hours or for a series of events to take place over multiple days. Devices should therefore be designed and rated for continuous protection against overvoltage.

<u>Any of the event durations on this plot could be damaging to improperly protected CCE.</u>

[1] The leftmost bar representing the interval 0-5 minutes contains 1037 events out of a total 3004 in that bar that are 10 seconds long. Some of these represent large voltage changes for brief periods, and some are from the line voltage varying around the 350 V threshold of our analysis, sometimes crossing above it for a 10-second period before dropping below again (431 of these 10-sec events end with the voltage dropping ≤ 5 V).

[2] In many cases, overvoltage events occur within a short period of time of each other, as even a short dip below 350 V will cause a new overvoltage event by the definition used here. See page 11 for an example where a period of erratic overvoltages results in numerous shorter-duration ‘events’ because of short dips below the 350 V overvoltage threshold.

CONCLUSIONS

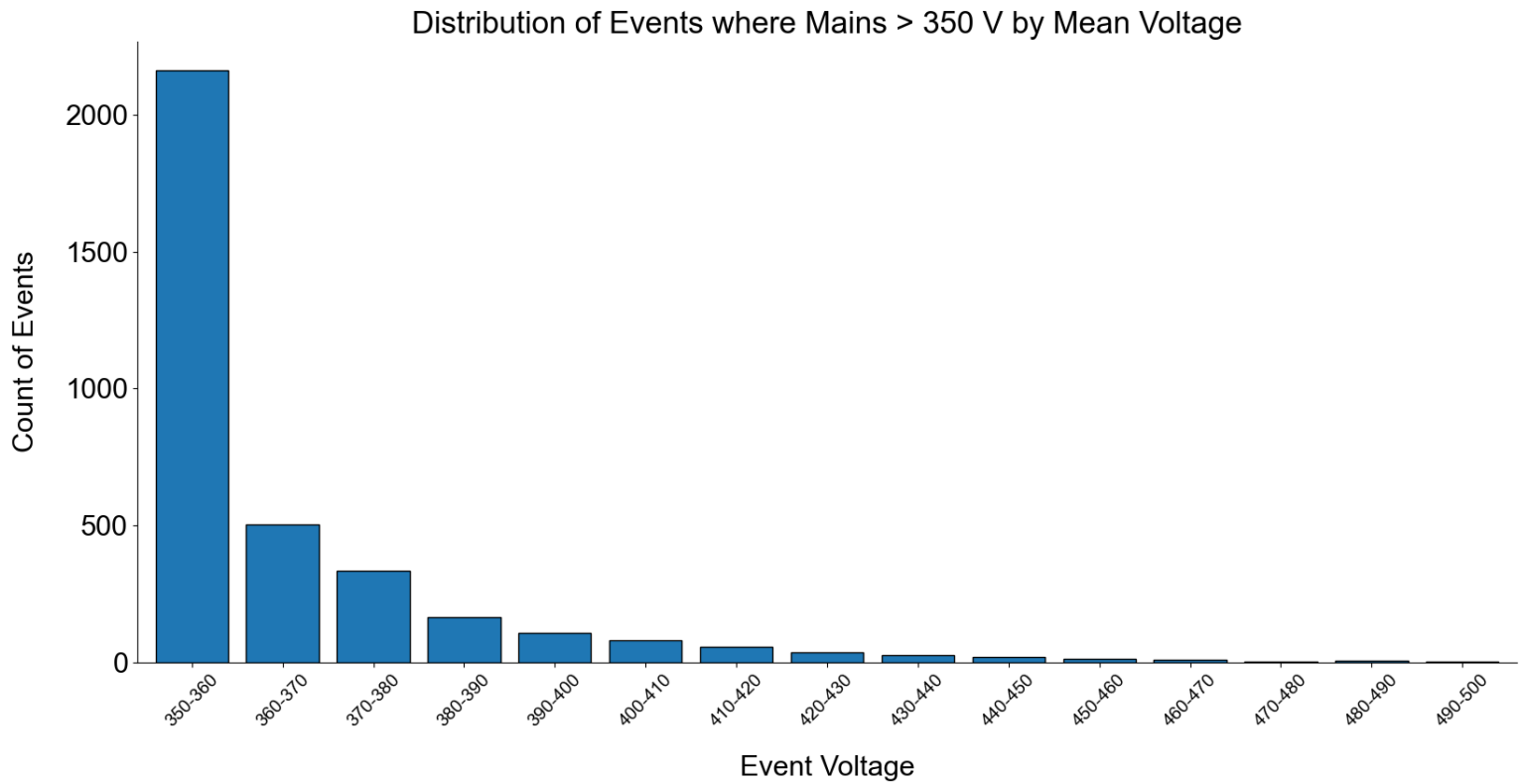
- **New Horizons and country collaborators have analyzed a longitudinal voltage dataset collected from vaccine refrigerators in 347 locations in Kenya and Nigeria, representing a total of 293,654 facility-days of voltage data.**
- **These analyses indicate that 8% of facilities experienced a voltage event in excess of 415 V, and for robust field performance, voltage stabilizers should be designed to properly withstand voltages in excess of 500 V.**
- **Most overvoltage event durations (periods of time where voltage is continuously above 350 V) are between 10 seconds and 10 minutes in duration, but some last multiple hours or even days.**
- **As additional time passes, additional facilities will experience challenging overvoltage events; for projecting potential failure rates, the 10-year design life for CCE should be considered rather than just the ~2.3-year period of data collected here.**
- **New Horizons is available to discuss these results and implications for specifications and designs with regulators and designers of equipment.**

We would like to thank the National Vaccines and Immunization Program (NVIP) in Kenya and the National Primary Health Care Development Agency (NPHCDA) in Nigeria for support of this work.

APPENDIX A: OVERVOLTAGE EVENTS BY MEAN VOLTAGE

This plot shows all the events where the voltage was above 350 V, categorized by the mean voltage. It is similar to the plot on page 6, but this one accounts for each event, rather than only counting the maximum voltage for a fridge. It is also based on the mean voltage over the duration of the event rather than the peak of the event.

Not surprisingly, there are a greater number of events at lower voltages than higher voltages.

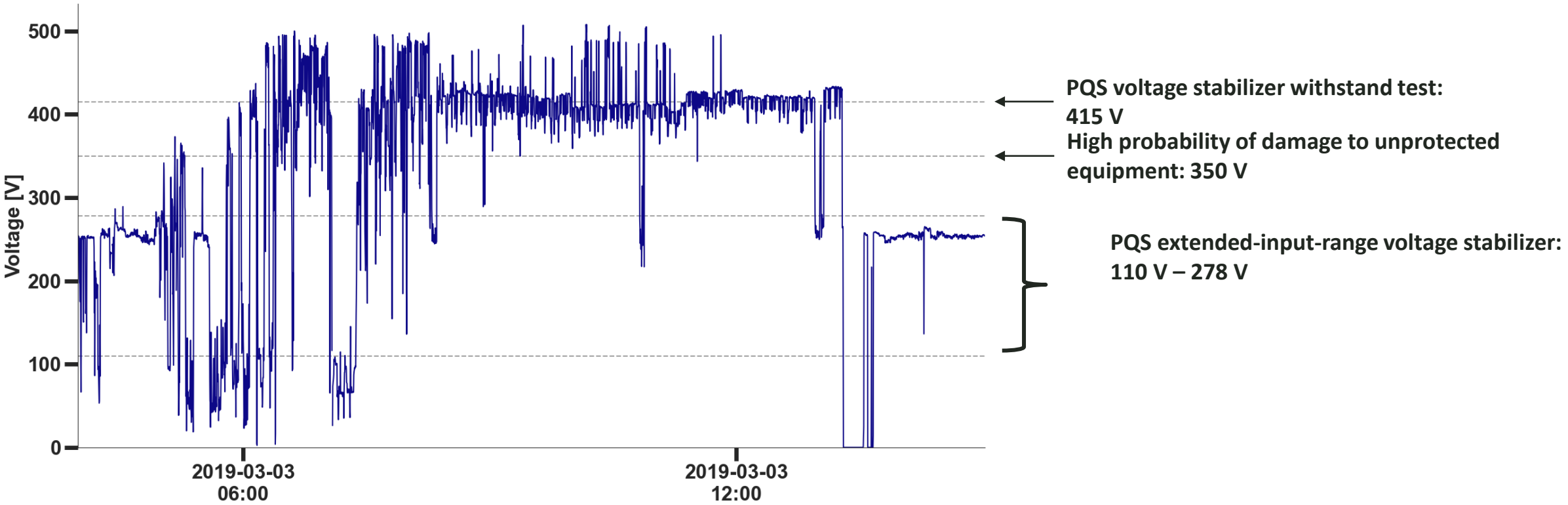


Appendix B: Time-Series Plots

Example time-series plots of overvoltages at facilities

Note: Each page shows a different facility

MAXIMUM VOLTAGE IN STUDY



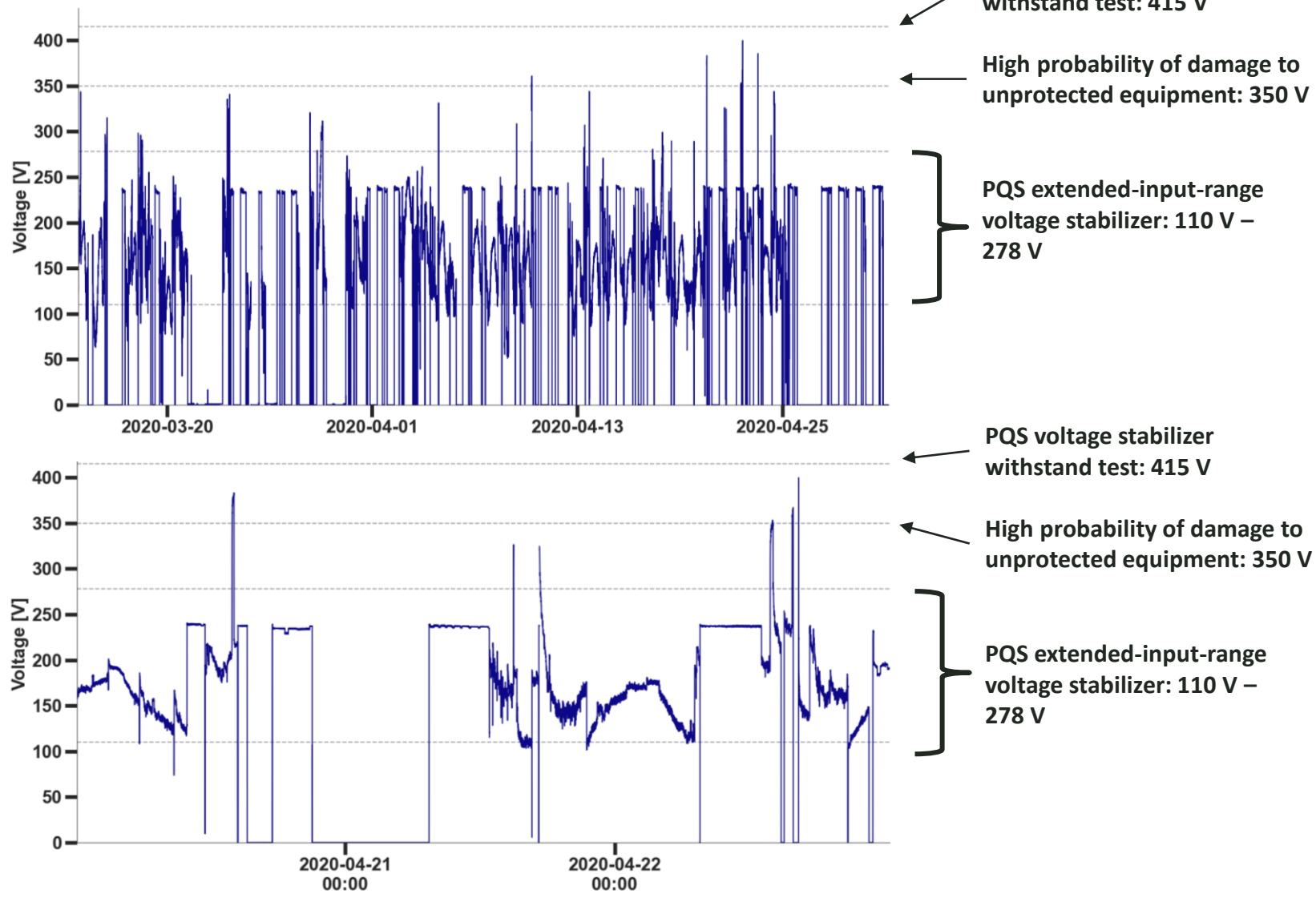
Overvoltage events lasting approximately 8 hours including a maximum voltage of 507 VAC, at a health facility in Kenya. This period amounts to 78 "events", or transitions above the 350 V threshold.

CHRONIC OVERVOLTAGE AND UNDERFREQUENCY

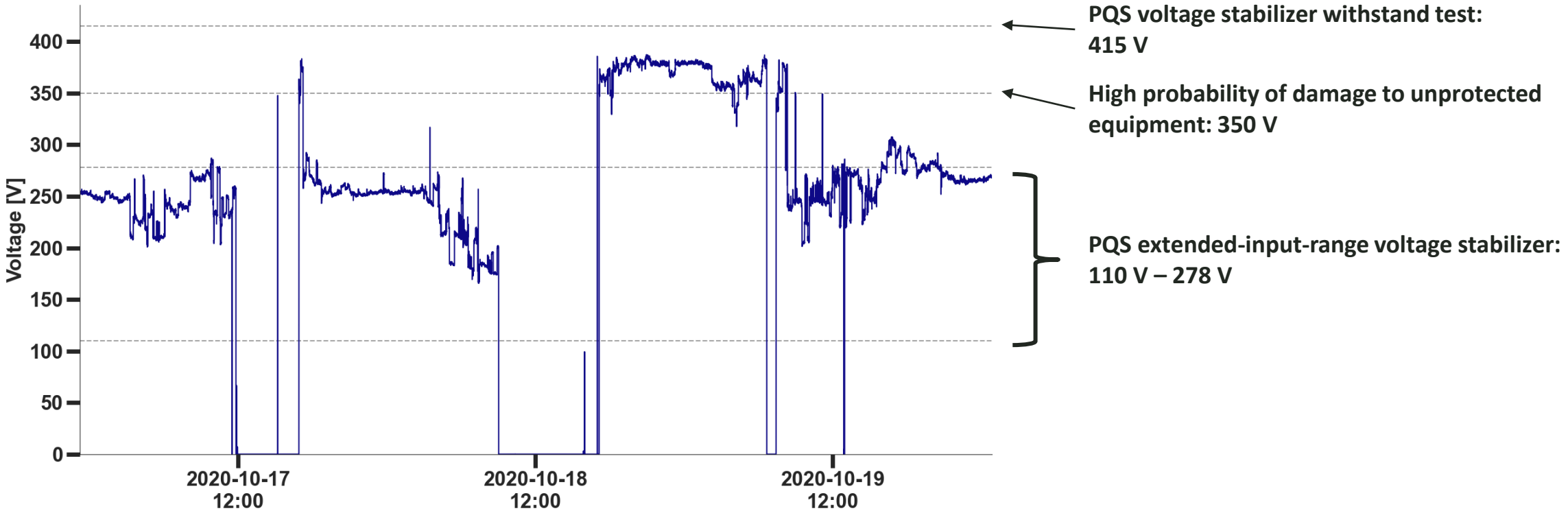
Both grid and generators are used to power health facilities, and each can have voltage or frequency regulation issues:

This site is a hospital in Nigeria that is probably using both grid and generator and has chronic overvoltage problems. During the 6-week period in the upper plot, there were 6 events > 350 V, and many between 300-350 V, too. The lower plot is zoomed in on 3 days near the end of the upper plot, including a peak of 381 V. The maximum voltage at this site occurred about six months earlier: 447 V.

The presumed grid voltage is varying relatively slowly over the course of a day, from 110 V to 290 V, shown better in the lower plot. During these times, frequency is 50 Hz. The flat periods around 240 V have frequency of 45 Hz, which is considered underfrequency and can cause stress on compressors. We presume the 45 Hz portions are during operation from a generator.



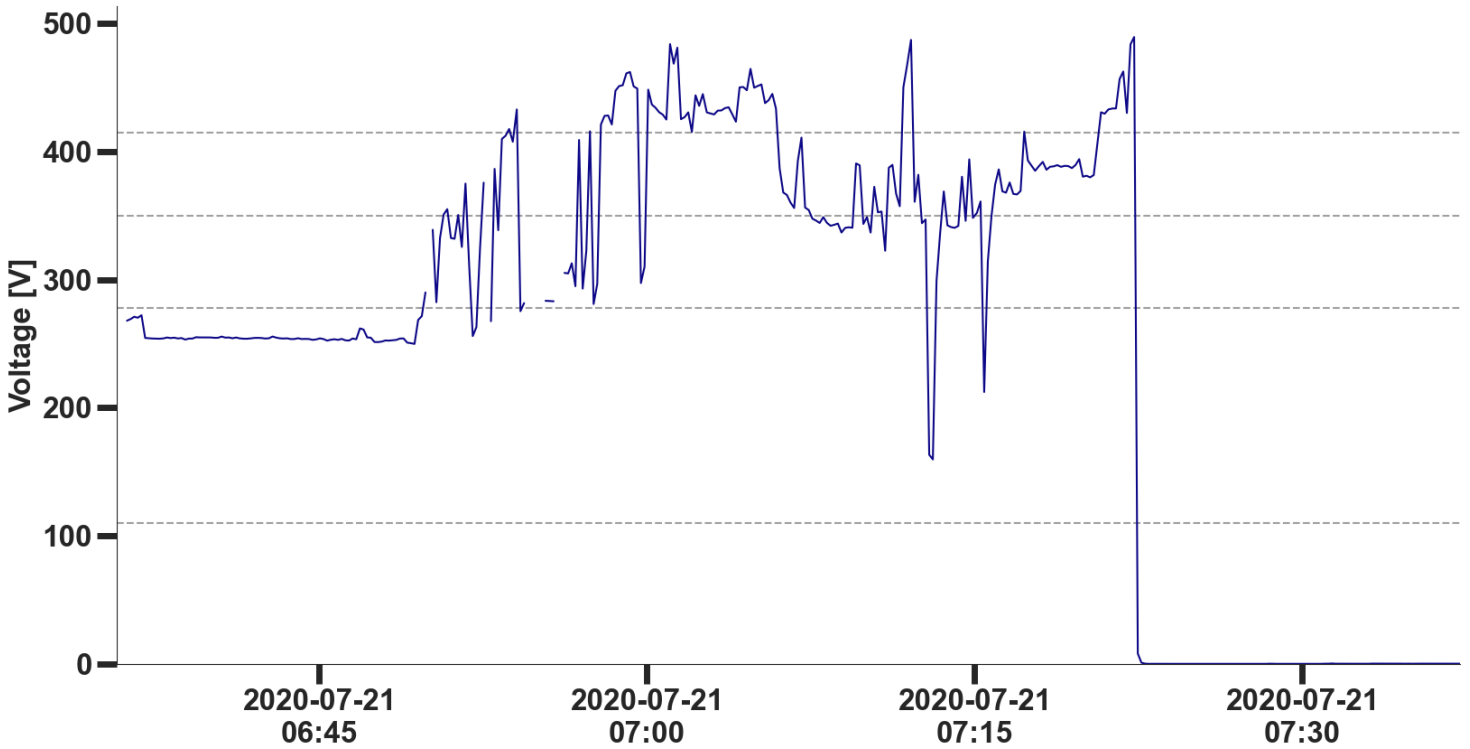
CHRONIC OVERVOLTAGE



This facility in Kenya has chronic overvoltage. Its voltage was approximately 290 V most of 2020, and it had at least one event with voltage > 350 V event every month in 2020 except April. All events were < 400V, except a single 10-second average voltage of 434V on 2020-03-04.

Because overvoltage events recur at this location, if the facility replaces a damaged device, the replacement is likely to be damaged soon.

EXAMPLE V > 415 V



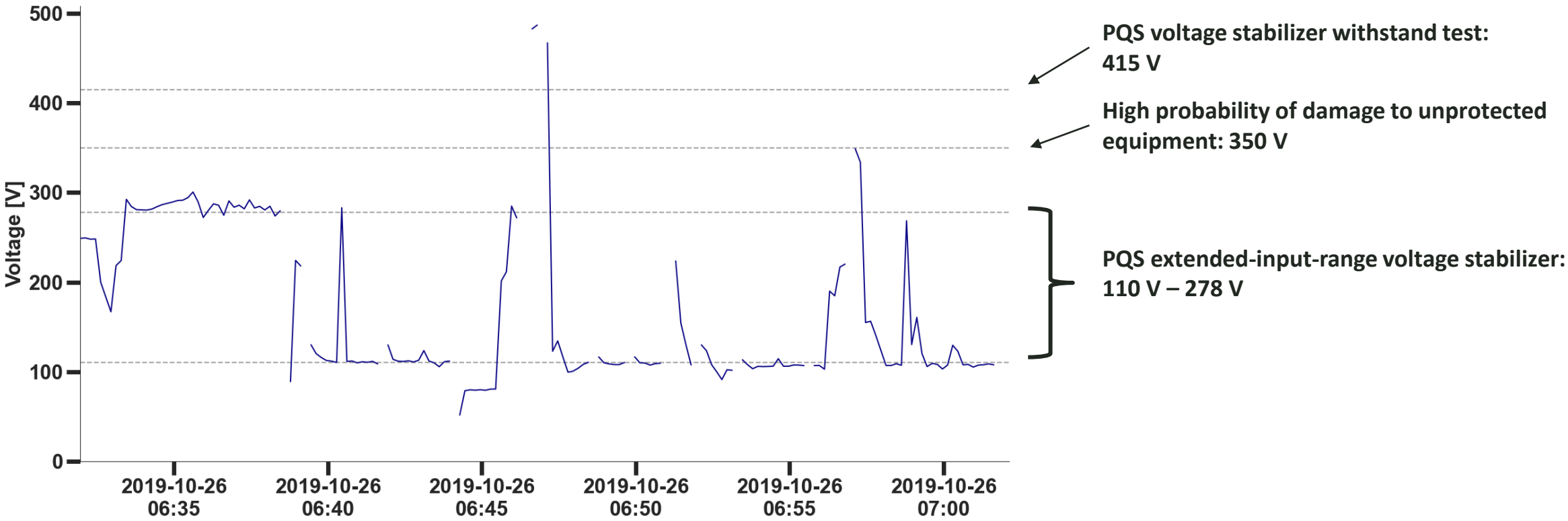
PQS voltage stabilizer withstand test: 415 V

High probability of damage to unprotected equipment: 350 V

PQS extended-input-range voltage stabilizer: 110 V – 278 V

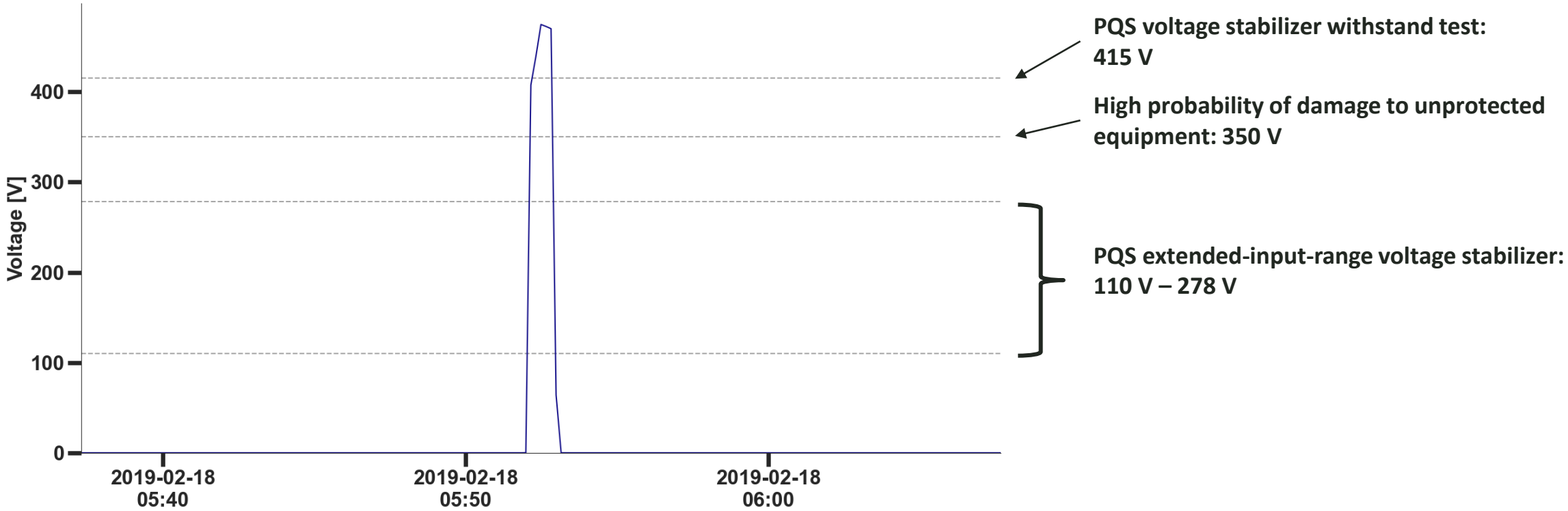
This facility in Kenya experienced a series of events over 350 V, up to a maximum of 487 V.

RAPID, LARGE VOLTAGE SWINGS



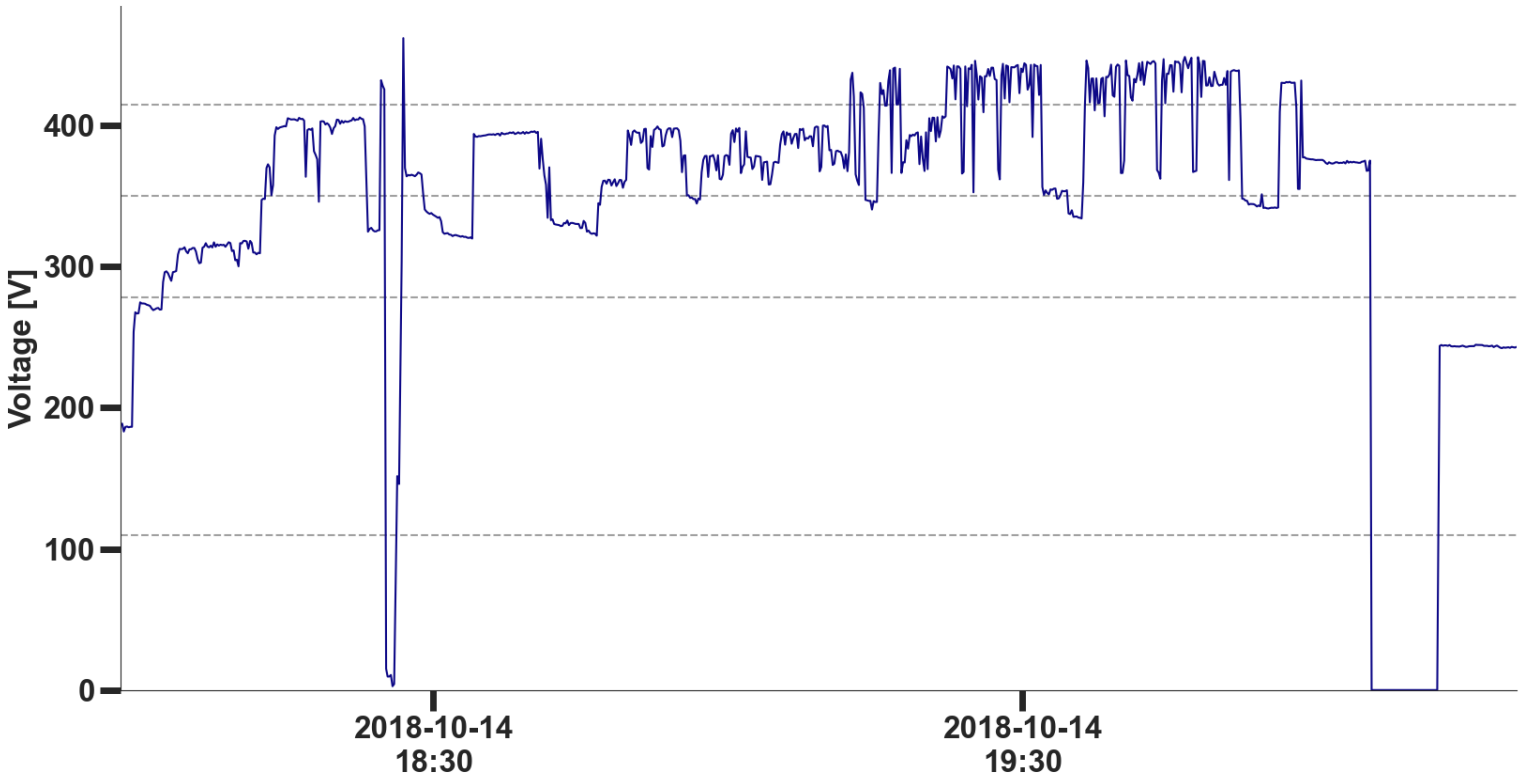
This facility in Kenya experienced up to 487 V. This half-hour period is part of a 14-hour period where the voltage varied from 0 V to 487 V, sometimes with steps from 180 V to 330 V and back within 20 seconds.

EXAMPLE V > 415 V



This facility in Kenya experienced this 40-second period of up to 475 V during a 4-hour period where the voltage was otherwise close to zero. In March of the same year, there was a 5-minute period up to 464 V and in June a day-long series of events up to 464 V.

EXAMPLE SERIES OF OVERVOLTAGE EVENTS



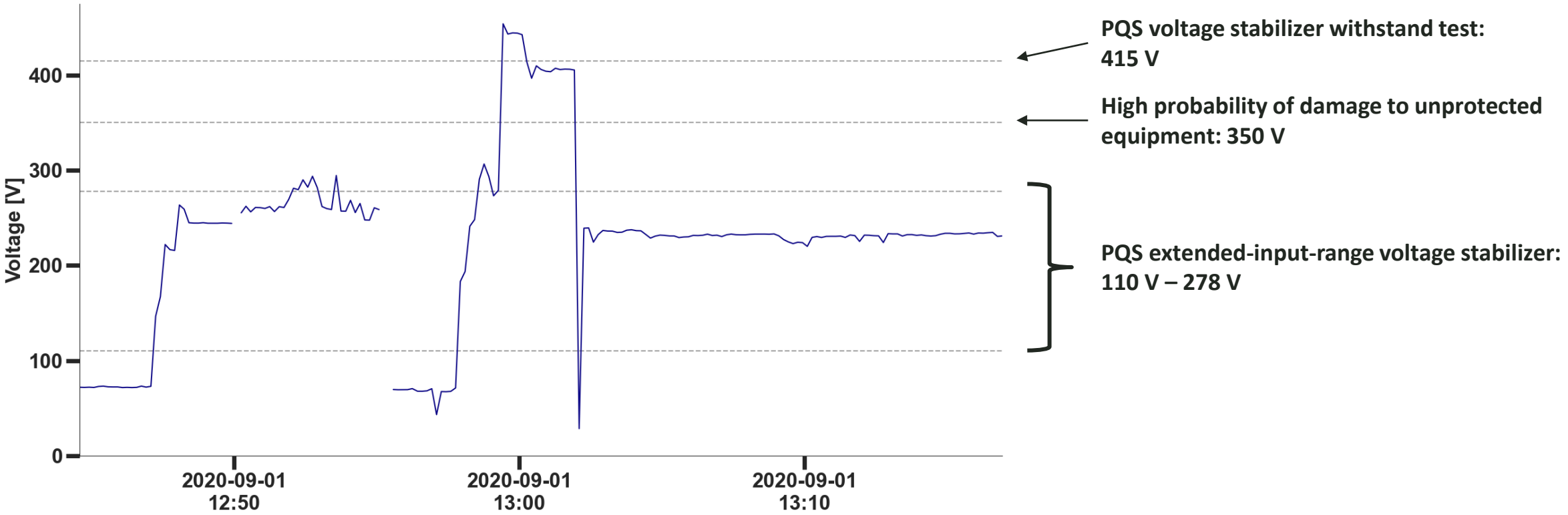
PQS voltage stabilizer withstand test: 415 V

High probability of damage to unprotected equipment: 350 V

PQS extended-input-range voltage stabilizer: 110 V – 278 V

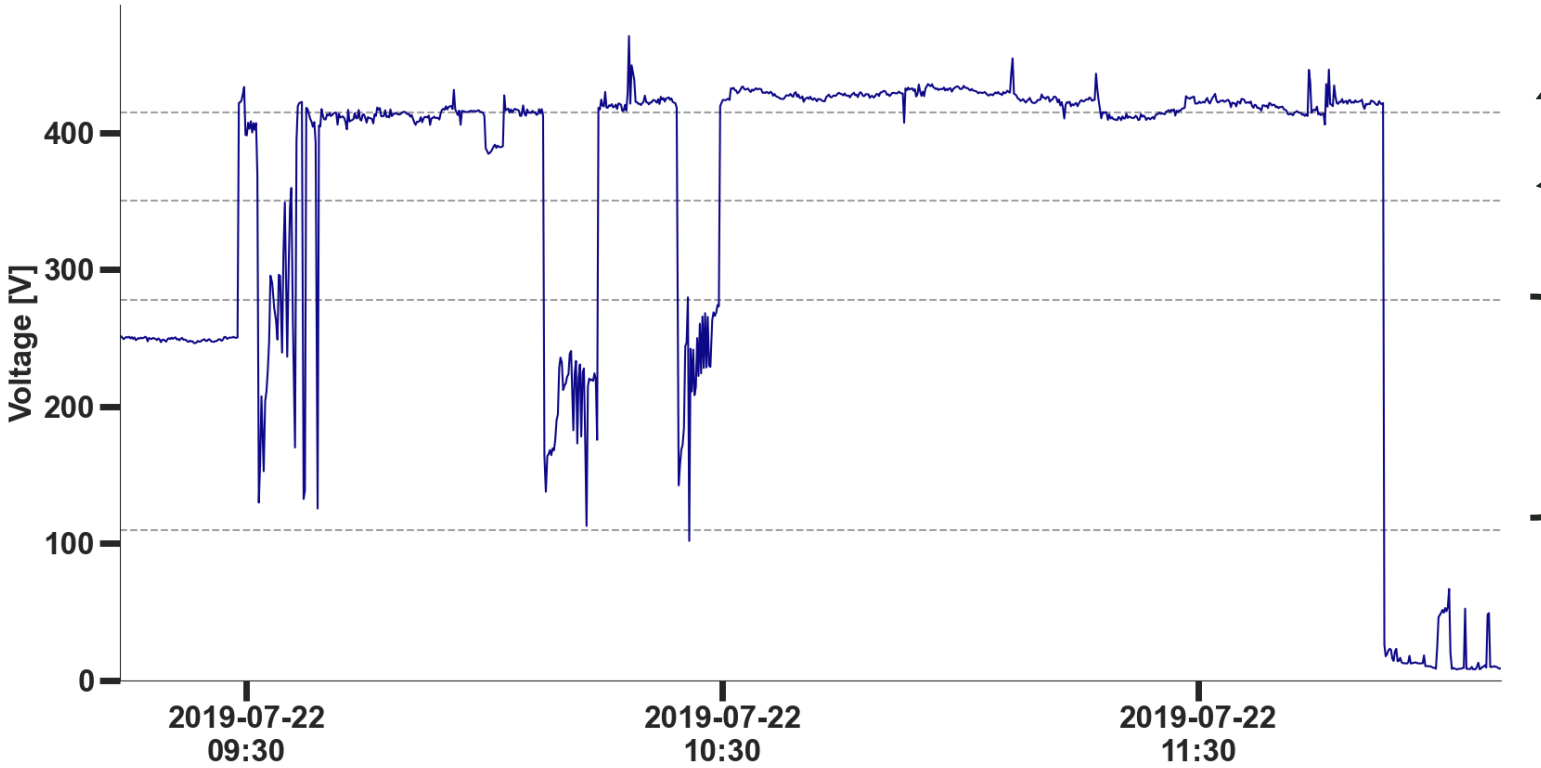
This facility in Kenya experienced two hours of events up to 456 V.

EXAMPLE V > 415 V



This facility in Kenya experienced 150 seconds at over 400 V, going to 454 V at its maximum.

EXAMPLE LONG-DURATION OVERVOLTAGE



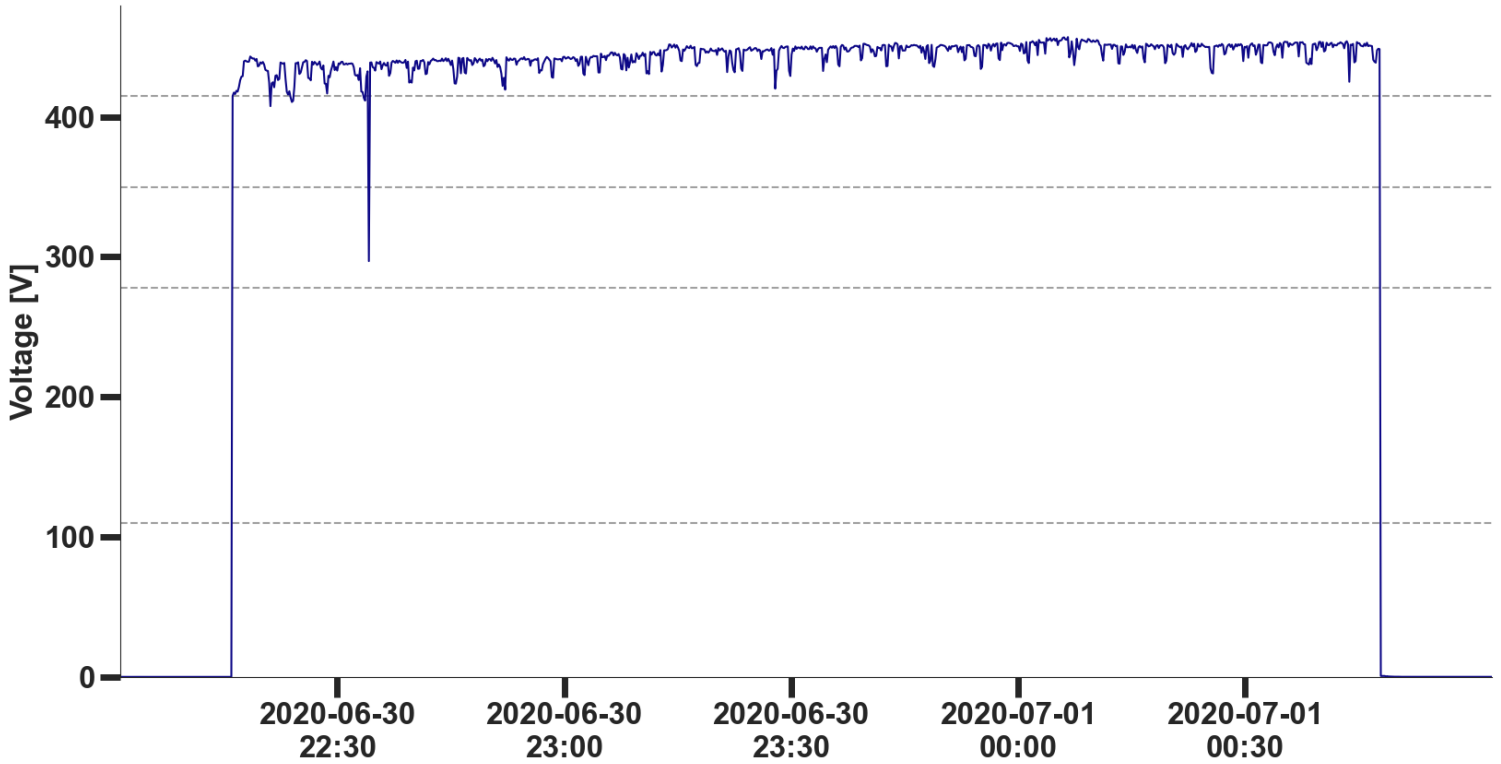
PQS voltage stabilizer withstand test: 415 V

High probability of damage to unprotected equipment: 350 V

PQS extended-input-range voltage stabilizer: 110 V – 278 V

This location in Kenya had about 2.5 hours of events up to 456 V.

LONG-DURATION OVERVOLTAGE



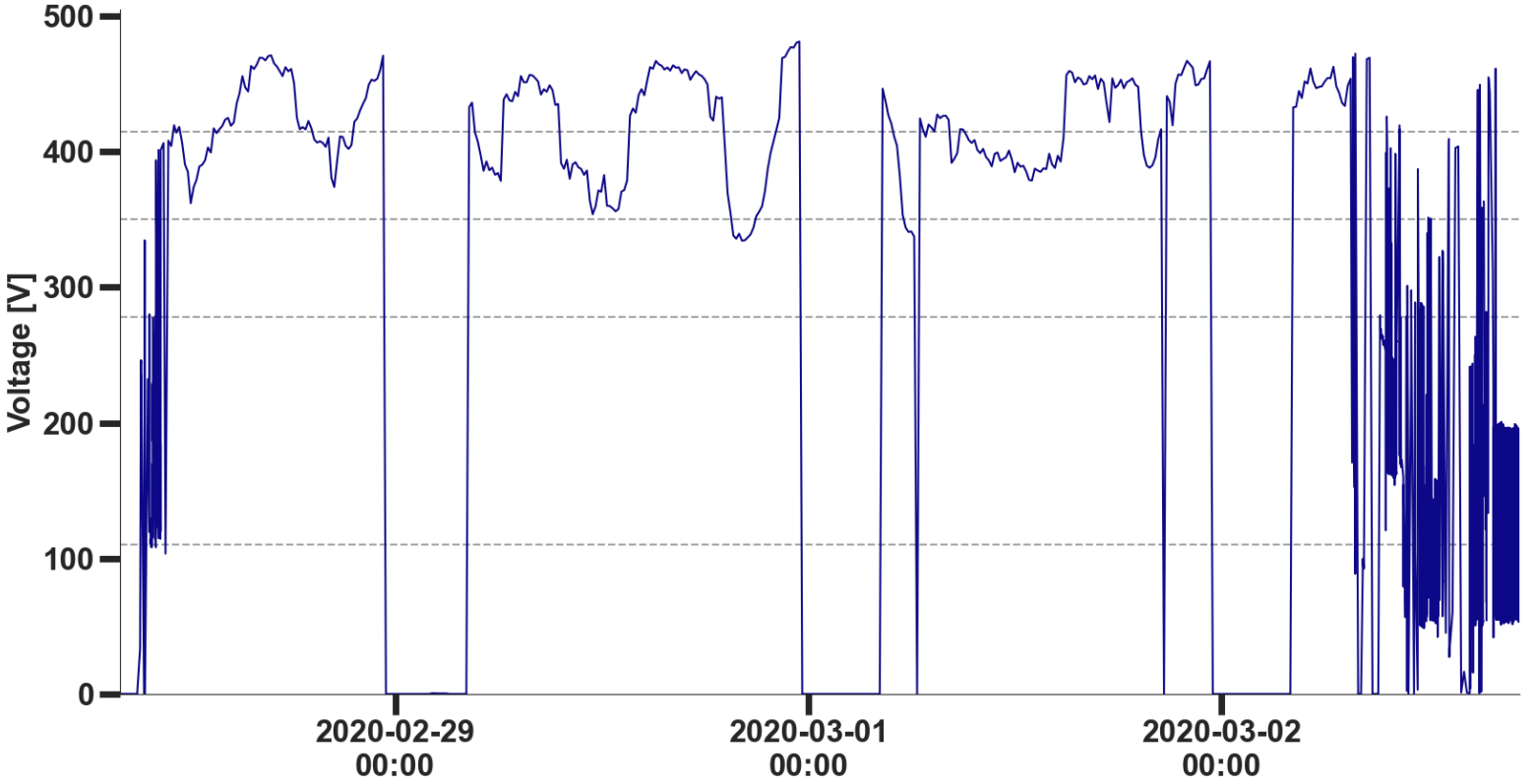
PQS voltage stabilizer withstand test: 415 V

High probability of damage to unprotected equipment: 350 V

PQS extended-input-range voltage stabilizer: 110 V – 278 V

This health facility in Nigeria experienced up to 456 V during this 2.5-hour period.

VARIABLE VOLTAGE FROM 0 V TO 481 V



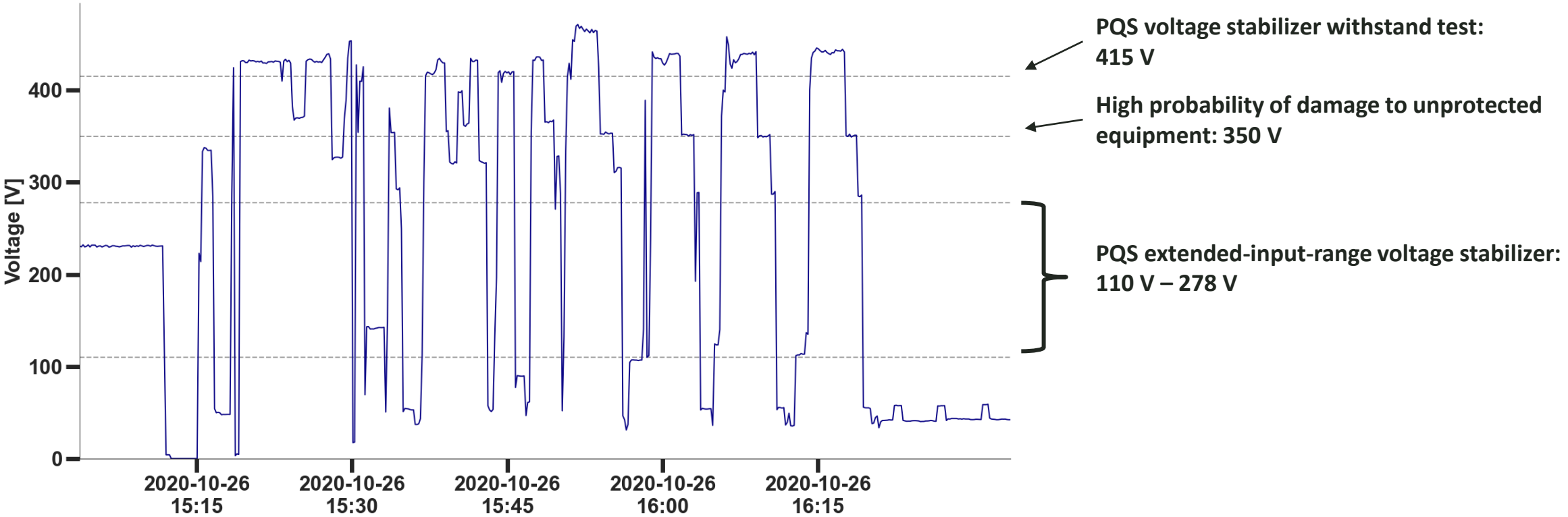
PQS voltage stabilizer withstand test: 415 V

High probability of damage to unprotected equipment: 350 V

PQS extended-input-range voltage stabilizer: 110 V – 278 V

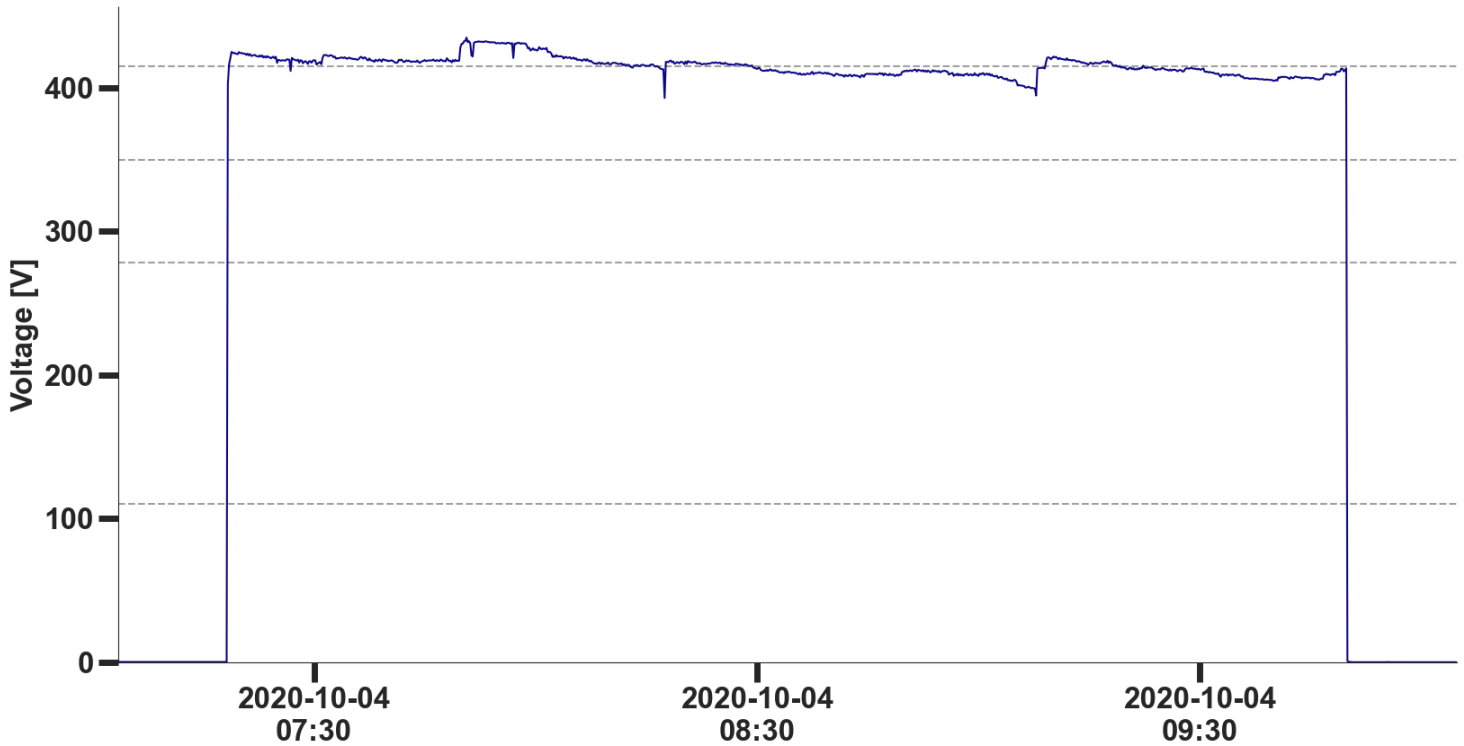
A period of 4 days at a facility in Nigeria where the voltage varied from 0 V to 481 V.

STEPS BETWEEN UNDERVOLTAGE AND OVERVOLTAGE



This facility in Nigeria experienced a series of jumps between undervoltage and extreme overvoltage for about an hour, cresting at 471 V.

LONG-DURATION OVERVOLTAGE



PQS voltage stabilizer withstand test: 415 V

High probability of damage to unprotected equipment: 350 V

PQS extended-input-range voltage stabilizer: 110 V – 278 V

This facility in Nigeria experienced roughly 2.5 hours of voltage between 390 V and 435 V.