PNNL-36684

Evaluating a Commercial Dynamic Line Rating Software with the National PMU Dataset

September 2024

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Prepared for the U.S. Department of Energy
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Abstract

To accelerate the development of data-driven applications for power systems, the Department of Energy (DOE) supported the collection and curation of a synchrophasor dataset spanning two years of observations from transmission utilities across the US. This National PMU Dataset (NPDS) was anonymized and distributed to awardees of a DOE research grant under non-disclosure agreements (NDAs) but has also been retained at PNNL to enable further research. Agreements with data contributors prevent the data from being shared outside the organization. However, establishing a blind research validation methodology is envisioned to maximize the value proposition of the NPDS. In this validation strategy, researchers may share algorithms/software (potentially as executables to protect intellectual property) with PNNL, and PNNL will share feedback about the software's performance on subsets of the NPDS. Such a blind methodology ensures that sensitive information about critical infrastructure remains protected, but the value of the NPDS can be extended to research beyond PNNL.

Through iterative feedback, the algorithms may be tweaked to address real-world artifacts. As the NPDS data is temporally and geographically diverse, it may capture features absent in smaller datasets used during the development of the algorithm under test. This report presents lessons learned from applying the blind validation methodology to LineID™, a synchrophasor-based dynamic line rating software developed by Topolonet Corporation. Improvements made to the software through iterative feedback, limitations of the validation methodology, as well as how the limitations of the NPDS affected the evaluation process are discussed. Observations indicate that the proposed validation methodology can be valuable for evaluating other tools in the future.

1.0 Introduction

To accelerate data-driven research in power systems, the Department of Energy (DOE) sponsored efforts to collect and aggregate two years of synchrophasor data sourced from transmission system operators across the United States [Banning et al., 2021]. This National PMU Dataset (NPDS) is unique in its geographic and temporal diversity and has immense potential to facilitate data-driven research beyond the accomplishments of the awardees of the initial DOE research grant [Biswas et al., 2022]. At the same time, the dataset has limitations- details about the data collection process, instrument configuration, and network topology is not available, and the data cannot be shared outside PNNL due to non-disclosure agreements (NDAs).

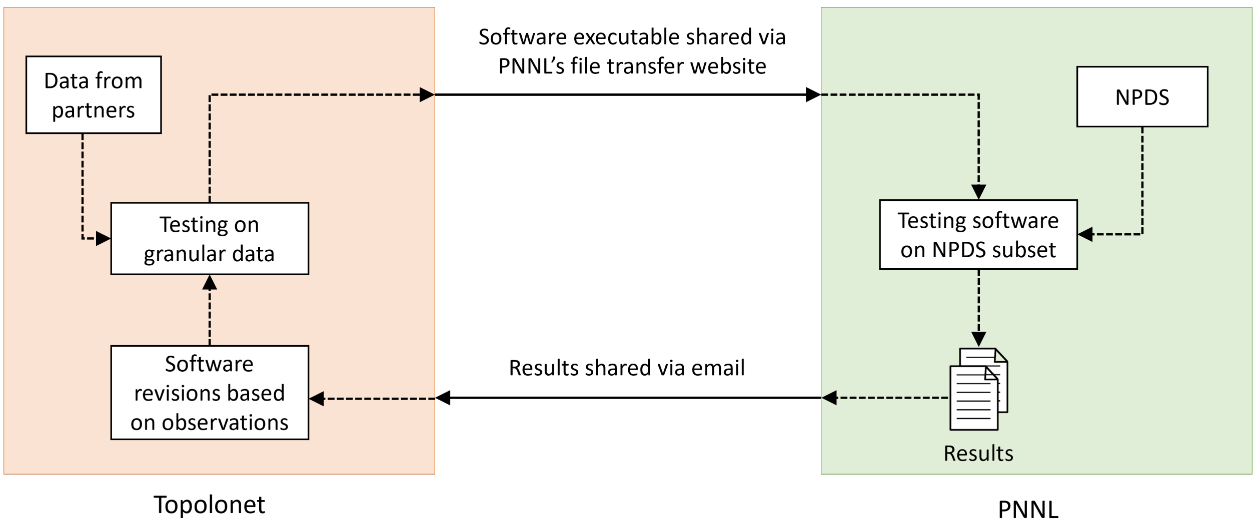

Figure 1: Proposed blind research validation methodology

To maximize data utility within said constraints, establishing a blind research validation methodology was pursued. In this strategy (Fig. 1), researchers outside PNNL could share their code/software (possibly as an executable to protect intellectual property), and PNNL would check the performance of the software on a subset of the NPDS and share feedback. Although this process may appear cumbersome, it offers several benefits as listed below.

- Data from the NPDS is not shared outside PNNL, hence avoiding divulging information covered by NDAs.
- The NPDS is a massive dataset ($\sim$ 50 TB). Often, researchers may only need to check their algorithms on small subsets of the NPDS, perhaps corresponding to particular types of events. Transporting the NPDS and querying the dataset to find periods of interest will require expensive data transport, storage, and handling infrastructure in addition to significant time and effort. The blind validation methodology avoids this duplication of effort by leveraging the data handling infrastructure and capability already available at PNNL.
- The blind validation strategy also ensures that the algorithms under test are not overfitted to the data they are being tested on, to improve generalizability to unseen data.

This report presents findings from applying the proposed blind evaluation strategy to LineID™, a synchrophasor-based dynamic line rating (DLR) software developed by Topolonet Corporation[1].

[1] https://topolonet.com/

The report does not intend to endorse or dismiss the LineID^{TM} product. Instead, the focus is on reporting if/how the iterative feedback process benefited the product testing, and how the process may be improved to test/validate other algorithms or software in the future.

1.1 Research Approach

DLR seeks to optimize the usage of power transmission lines. Unlike static line ratings, which assign a fixed maximum capacity to transmission lines based on conservative estimates of worst-case conditions, DLR adjusts the capacity in real time based on actual environmental conditions and system performance. LineID^{TM}, Topolonet's DLR solution, utilizes phasor measurement unit (PMU) data from both ends of a transmission line to estimate series resistance, inductance, shunt conductance, capacitance, surge impedance loading (SIL), loadability, and line ampacity without needing weather information. At the time of the evaluation exercise, Topolonet's patent applications for their DLR technology were pending, and hence the double-blind evaluation methodology was important for protecting intellectual property.

The testing was carried out in two stages. In the first stage, several sets of hour-long data from the NPDS were processed with the LineID^{TM} software, and feedback about usability, computation speed, noisiness in outputs, etc. was provided. Based on feedback from the initial testing, Topolonet made improvements to the LineID^{TM} software, and a revised version of the tool was tested using 24-hour datasets from two 345 kV transmission lines of different lengths from the same transmission utility.

1.2 Dataset Limitations

As previously stated, the data in the NPDS is not accompanied by network models and other details about line configuration or instrument details. Some information about the location of PMUs was available to PNNL, from which the length of the lines was estimated. This was cross-checked with the Homeland Infrastructure Foundation-Level Data (HIFLD) dataset maintained by the US Department of Homeland Security [DHS, 2024]. However, no information was available about how neutral conductors were connected, what grade of PMU/instrument transformers were used, if shunt capacitors were placed between two ends of the transmission line being examined, etc. These configuration details can impact line parameter estimation, so the present evaluation was limited by the lack of such information. To ensure that the parameter estimates were reasonable, several qualitative aspects were checked, such as:

- If the parameter estimates obtained were consistent across seasons
- If observed trends in parameter estimates could be explained by changes in power flow, time of day, difference in line lengths, weather conditions, etc.
- If parameter estimates were consistent in the presence of common power system disturbances, fluctuations in electrical quantities, etc.

Although information about PMU grade or manufacturer was not available, the PMUs utilized in this work were likely to be from the same manufacturer, experience similar weather conditions, and have similar measurement noise as they were located in the same geographical area and installed to monitor lines operated by the same utility. Therefore, consistent trends in parameters and estimation noise were expected from both lines.

2.0 Observations and Lessons Learned

The blind research validation exercise helped Topolonet identify and modify aspects of their algorithm to make the LineID^{TM} software capable of handling various situations encountered in real grid operations. This chapter briefly describes some of these improvements and presents parameter estimates obtained for two 345 kV transmission lines using the modified software.

2.1 Modifications to LineID^{TM}

Through iterative feedback, the major modifications made to LineID^{TM} are listed below.

- Several bugs related to time synchronization and missing data handling issues were identified and addressed.
- The underlying algorithm solves an optimization problem; hence, the specified tolerance dictates the optimization convergence accuracy. Higher tolerance increases the variance in results but also increases computation speed. Lower tolerance, on the other hand, provides smoother parameter estimates at the cost of computation speed. The tolerance parameter in LineID^{TM} was made tunable to meet the needs of systems with varying levels of measurement noise and data quality.
- LineID^{TM} has been modified to skip time windows in which the calculation errors are higher than 15%. The calculation error is defined as the percentage of the difference between values obtained from solving for the two sides of equations modeling the transmission line. Due to measurement noise and data artifacts, this error is non-zero. A low error value indicates the validity of the results obtained. Error values higher than 15% indicate that LineID^{TM} could not accurately estimate the parameters in the given time window due to data quality issues or high imbalance in the transmission line. This feature will prevent spurious results and obviate the need to use a smoothing filter on the results.
- LineID^{TM} has been modified to assign different error codes for data windows with high calculation error, large number of missing samples, non-convergence of the algorithm, etc. The error codes made debugging and diagnosis easier.
- Capability to handle bidirectional power flow has been added to the software. It was also observed that power flow direction reversal often occurs over a period of hours and is accompanied by very low power transfer on the line. LineID^{TM} uses line currents to obtain parameter estimates, and hence low power flow can adversely impact estimation accuracy.
- Possible existence of shunt reactors seen by the PMUs has been considered, and a mathematical model of the transmission line with shunt reactors at both sides of the line was devised and implemented in LineID^{TM}.
- It was observed that the algorithm, in special circumstances, converged to an unacceptable solution. This was most likely due to the highly ill-posed nature of the equations governing the transmission line that caused the algorithm to converge to an incorrect solution. A novel mathematical model has been devised to constrain the algorithm in a smaller search domain where the correct solution exists.

2.2 Results from PMU Data

As previously noted, data from two 345 kV transmission lines (Line A: $\sim$25 miles, Line B: $\sim$100 miles) was used to evaluate the LineID™ software. Available PMU data had a reporting rate of 30 frames per second (fps). The user can configure data window size and tolerance parameters. LineID™ allows a minimum window size of 2 seconds, and the tolerance may be varied between 10^{-2} and 10^{-8}.

In the tests in this work, the two parameters were chosen as 100 seconds and 10^{-6}, respectively. With this setup, parameter estimation for 24 hours took approximately 20 minutes on average across all the runs conducted. All tests were performed on an Intel Core i9-10885H, 2.40 GHz, 32 GB RAM PC.

2.2.1 Results for Line A

LineID™ was tested using three randomly chosen 24-hour data blocks from three different months in a year. The corresponding series resistance and inductance estimates (diagonal entries of the resistance and inductance matrices) obtained are shown in Fig. 2 and Fig. 3, respectively. One can observe that the inductance estimates obtained are consistent across the seasons. Some spurious spikes are noted in the estimates, but the magnitude of the spikes is quite low.

The series resistance estimates for the different periods also agree with each other, although the January values seem to be lower. This difference may potentially be explained by the fact that low winter temperatures lead to cooler conductors and lower resistance values. Additional investigation showed that on the January day examined in this work, a snowstorm was reported in the geographical vicinity of Line A.

As Topolonet's algorithm uses currents flowing through a transmission line to estimate its parameters, the results obtained may not be accurate when the line currents are low. This is because when currents are low, instrumentation errors and noise may be more dominant in the measurements, leading to erroneous estimation. However, as DLR becomes critical when power flow approaches maximum line capacity, this limitation of the algorithm does not hinder its practical applicability. This phenomenon is visible in the July resistance estimates in Fig. 2. Large fluctuations in resistance estimates are apparent towards the beginning and end of the day, and an inspection of the corresponding real power flow on this line (Fig. 4) shows that these erroneous estimates coincide with periods of very low power flow.

Fig. 5 shows the surge impedance loading (SIL) values computed for Line A. Calculating the "true SIL" is not straightforward. The true SIL is approximately calculated by the following equation:

$$SIL = \frac{V_{L-L}^2}{\mathcal{R}\{Z_c\}}, \tag{1}$$

where V_{L-L} is the positive sequence line-to-line voltage magnitude, and Z_c denotes the positive sequence characteristic impedance of the line. Mathematically, Z_c may be expressed as:

$$Z_c = \sqrt{\frac{R + j\omega L}{j\omega C}} \tag{2}$$

Here, R, L, and C are the positive sequence per-unit series resistance, series inductance, and shunt capacitance of the line, respectively. Determining the true SIL value using the above deterministic equations is difficult as the accurate values of R, L, and C are not readily available in existing systems. Moreover, as changing environmental conditions impact line parameters, the

SIL value is time-varying as well. LineID™ aims to address this gap by estimating line parameters from PMU data and using these estimates to compute SIL values in real-time.

A typical value of SIL for a 345 kV line with 1-1414 MCM ACSR conductor per phase is 320 MW [Gutman et al., 1979]. The values of SIL shown in Fig. 5 appear reasonable because they are close to but lower than this typical value. Of course, since the configuration of conductors in the transmission line is not known, the estimation accuracy cannot be quantified. Fig. 6 shows the line stability limit (loadability), capped at 3 times the estimated SIL value per the well-established St. Claire's line loadability curves [Gutman et al., 1979]. The stability limit is calculated with 30% stability margin equivalent to $\sim 40°$ angular displacement across the line, but this default stability margin setting may be modified by the user. It should be noted that the calculated SIL includes the reactance of the equipment at the sending and receiving ends of the line installed between the points of measurement. Line ampacity estimates, calculated based on the stability limit, are shown in Fig. 7.

2.2.2 Results for Line B

Results obtained for Line B for two randomly selected days in June and December are shown in Fig. 8 and Fig. 9. These months were chosen as this line had very low power flow on the other months checked, and reliable parameter estimates could not be obtained. Inspection of the figures shows that the line parameter estimates obtained are consistent across seasons, and the resistance values are slightly lower in December, perhaps due to colder temperatures. Significant differences in parameter estimates among the different phases can be observed after 9:00 PM in the December data. This may be explained by increased phase imbalance observed on both ends of Line B, as shown in Fig. 10. Further, the ratio between the parameter estimates obtained for Lines A and B appears to be consistent with the approximate ratio of their lengths. This observation increases confidence in the estimates provided by LineID™.

The SIL, line stability limit (loadability), and ampacity obtained for Line B are shown in Fig. 11-13. Note that the SIL values obtained for Line B are higher than those for Line A, even though their rated voltages are the same. This difference may be attributed to the differences in line parameters, due to factors such as varying transmission tower heights, conductor arrangement, terrain below the lines, and ambient weather conditions.

Fig. 11 also shows a drop in SIL between 1 AM and 5 AM in the June data. This drop could be due to the energization of shunt reactors that leads to a change in line voltages, although data to confirm whether such an event occurred is not available. Note that the LineID™ software was able to provide consistent line parameter estimates in the presence of an event that manifests as a step change in voltage.

2.2.3 Observations from X/R Ratio

At present, many prevalent SIL computation methods use the assumption that the transmission line is lossless. Literature suggests that a transmission line can be assumed to be lossless if the corresponding X/R ratio is greater than 10 [Gutman et al., 1979]. Fig. 14 and 15 illustrate the X/R ratio ($X = j\omega L$) for Line A and Line B respectively. Note that the X/R ratio for Line A is well below 10, and can drop below 10 for Line B as well depending on environmental conditions. Hence, the lossless assumption is not always valid for both the lines examined.

A comparison between the X/R ratio of the two lines reveals that Line-B should have a higher SIL, stability limit and consequently ampacity. This is because the X/R ratio is much higher in Line B than it is in Line A, which shows that Line A is more lossy than Line B. This hypothesis is supported by the higher SIL, loadability, and ampacity values obtained for Line B (Fig. 11-13).

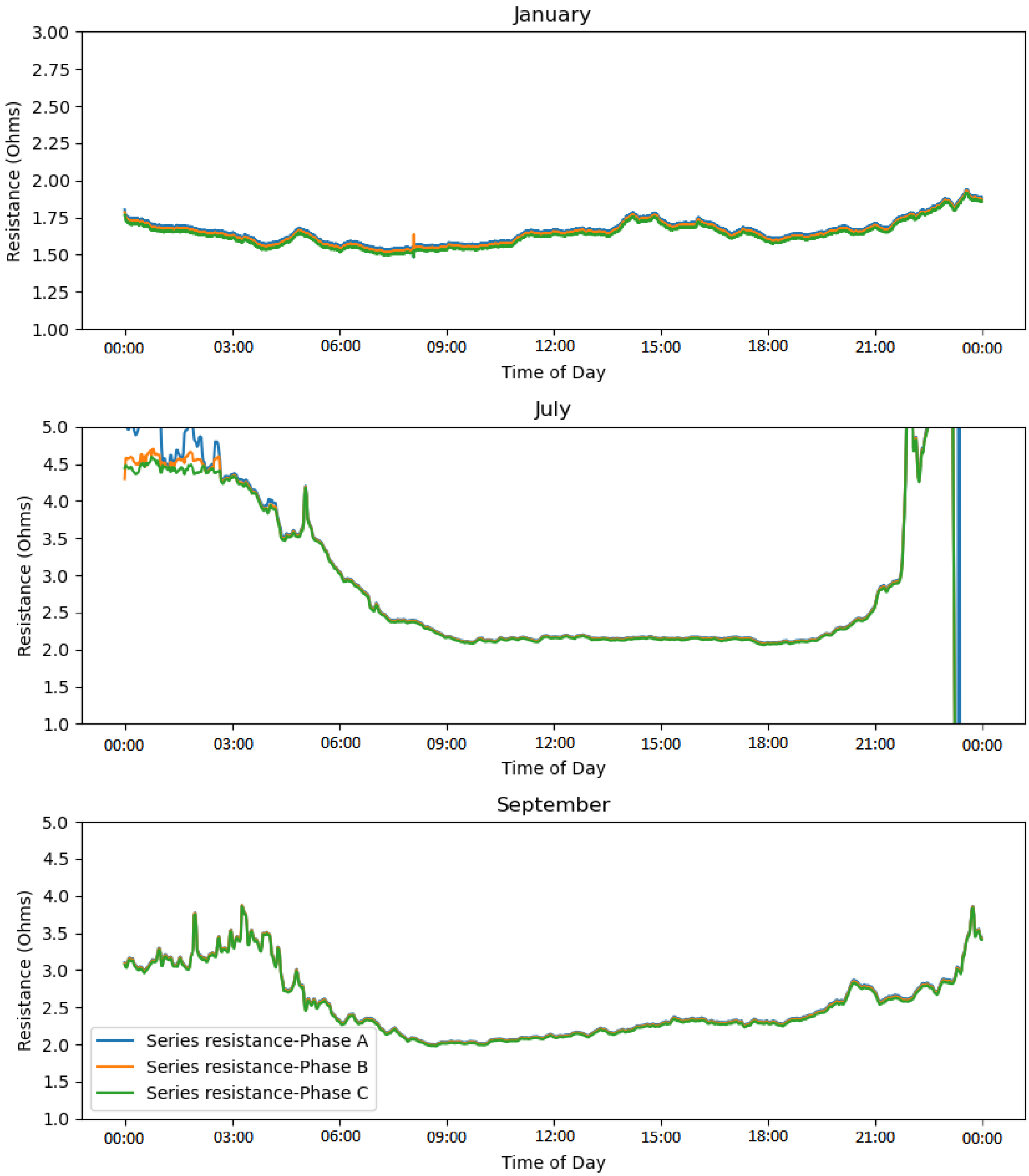

Figure 2: Series resistance estimates obtained for Line A. The x-axis indicates local time.

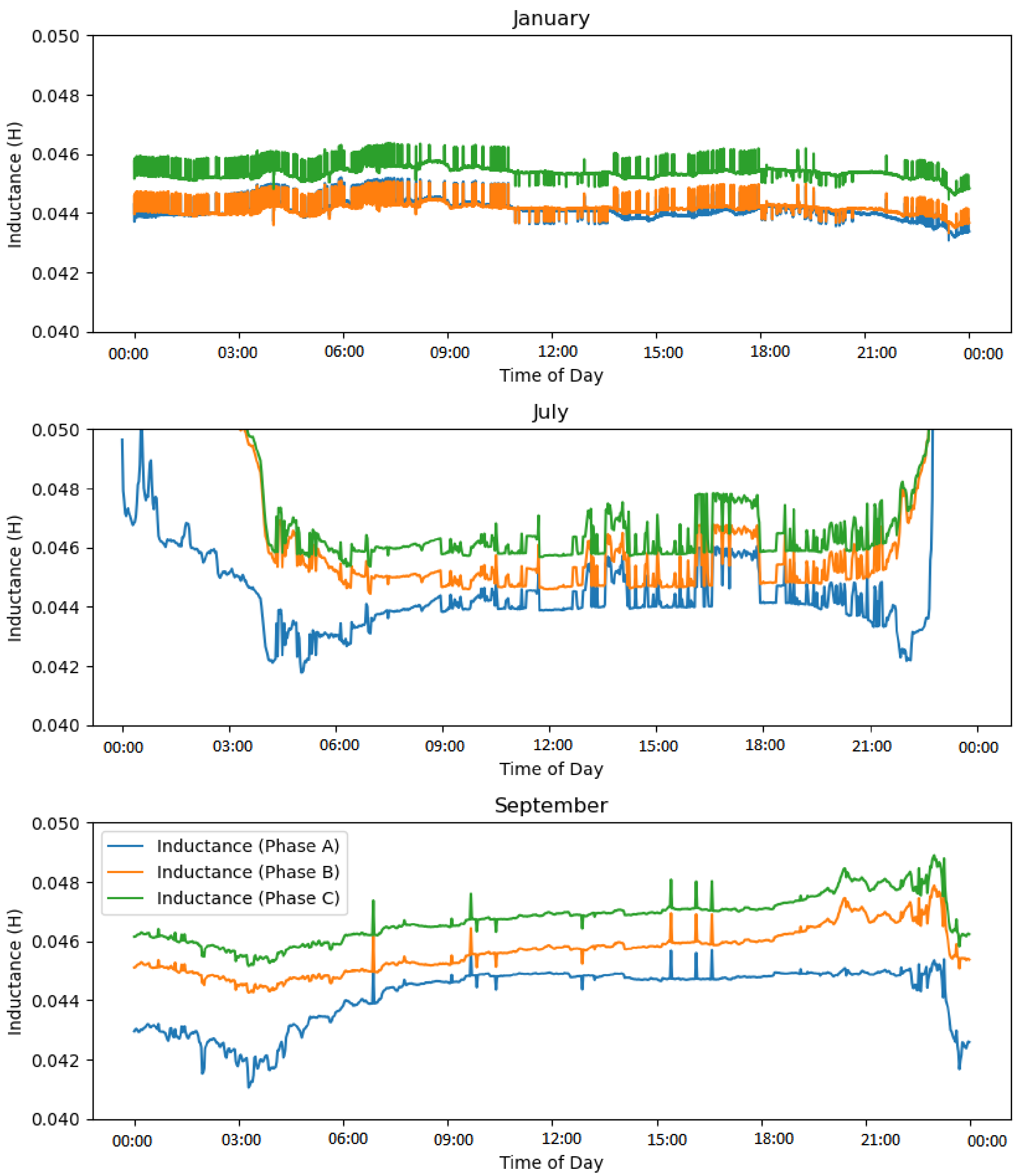

Figure 3: Inductance estimates obtained for Line A. The x-axis indicates local time.

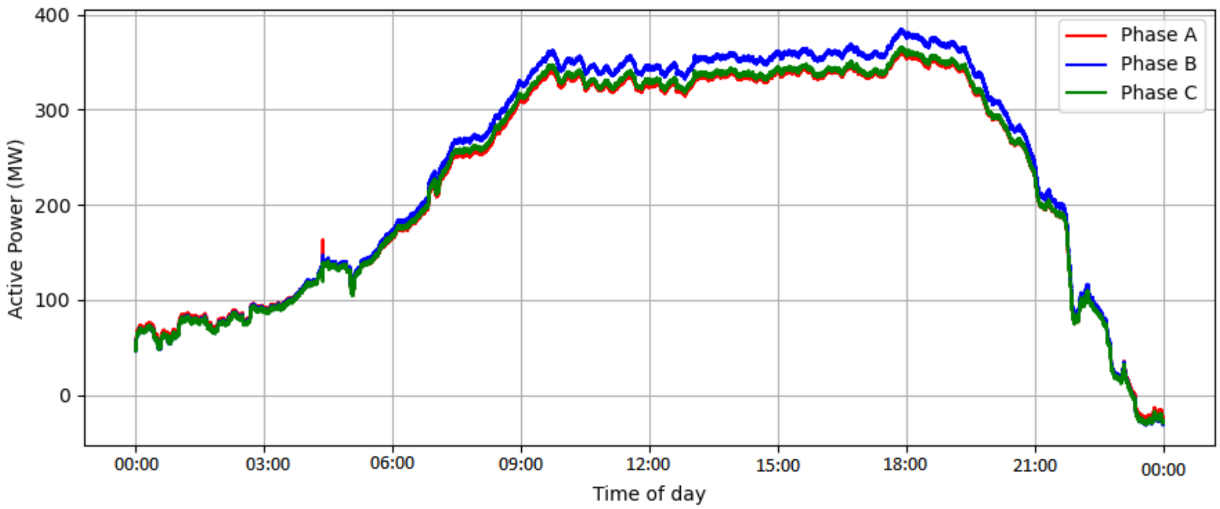

Figure 4: Power flow on Line A for the July day examined. The x-axis indicates local time.

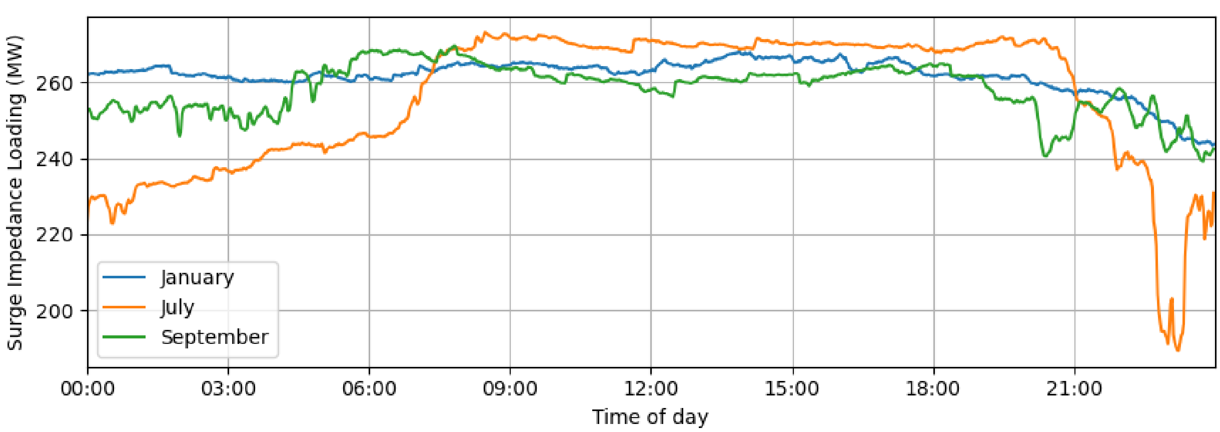

Figure 5: SIL estimates obtained for Line A. The x-axis indicates local time.

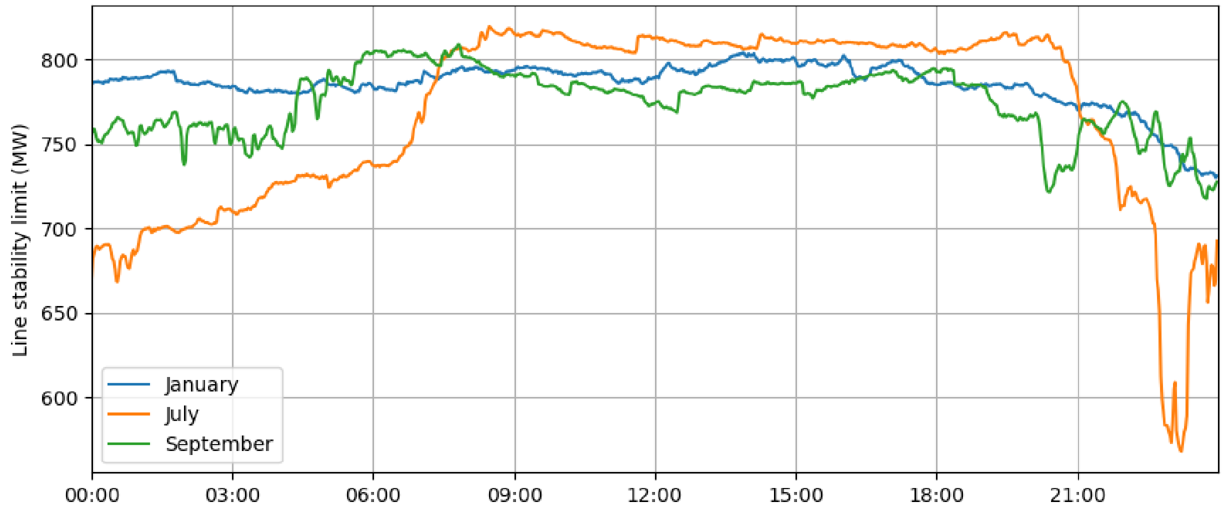

Figure 6: Line stability limit (loadability) estimates obtained for Line A. The x-axis indicates local time.

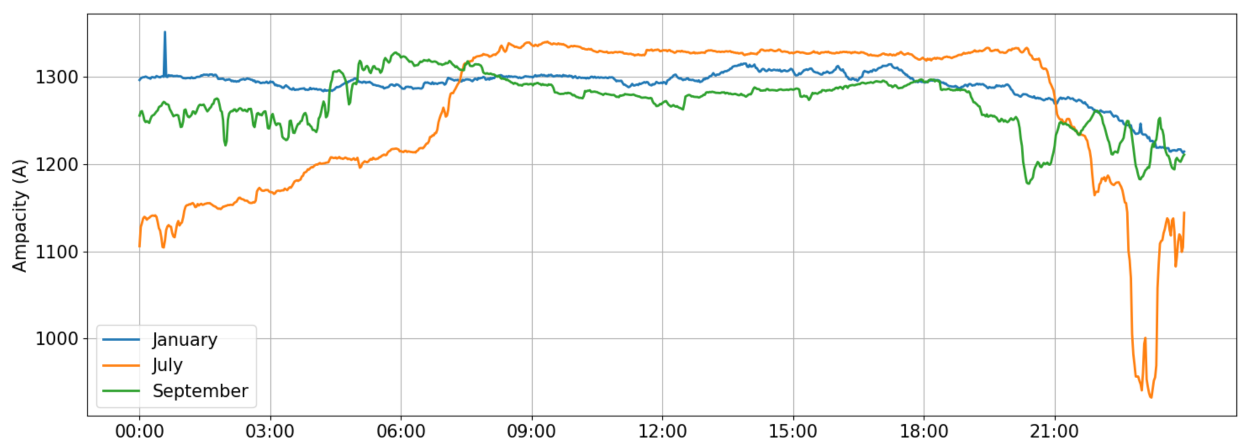

Figure 7: Line ampacity estimates obtained for Line A. The x-axis indicates local time.

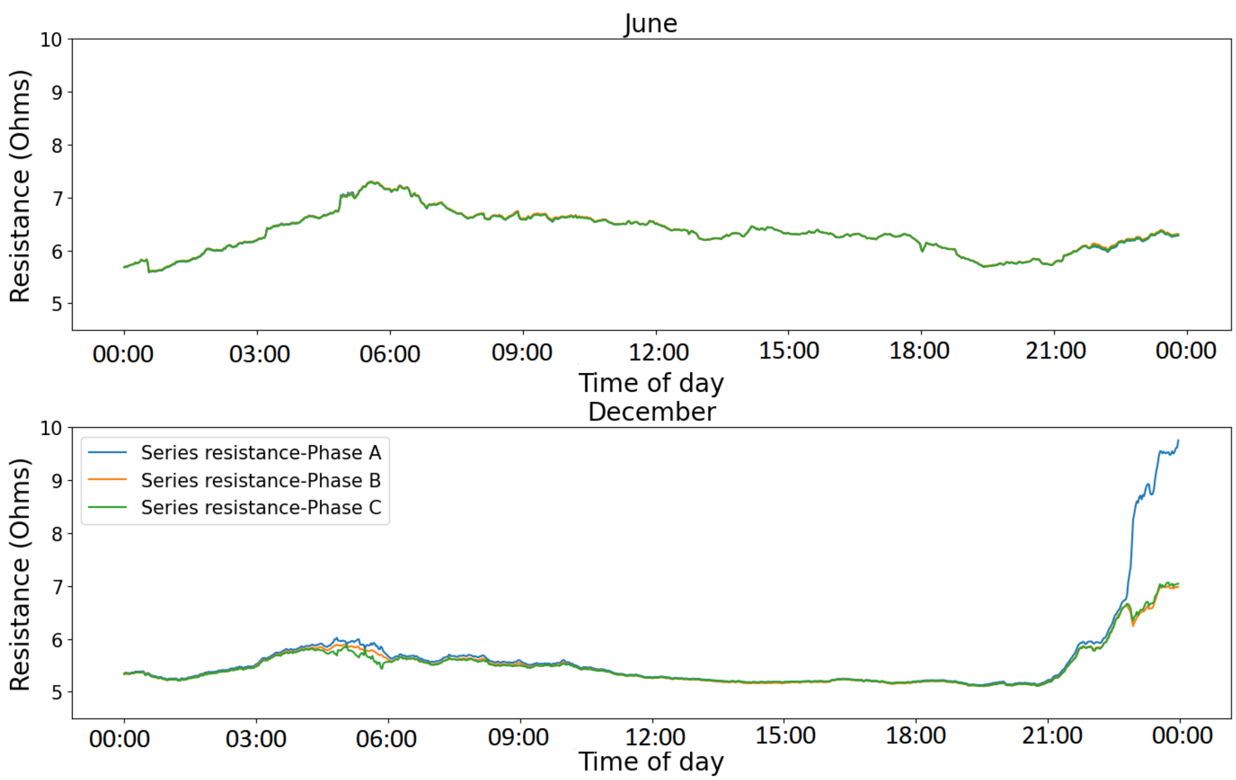

Figure 8: Resistance estimates obtained for Line B. The x-axis indicates local time.

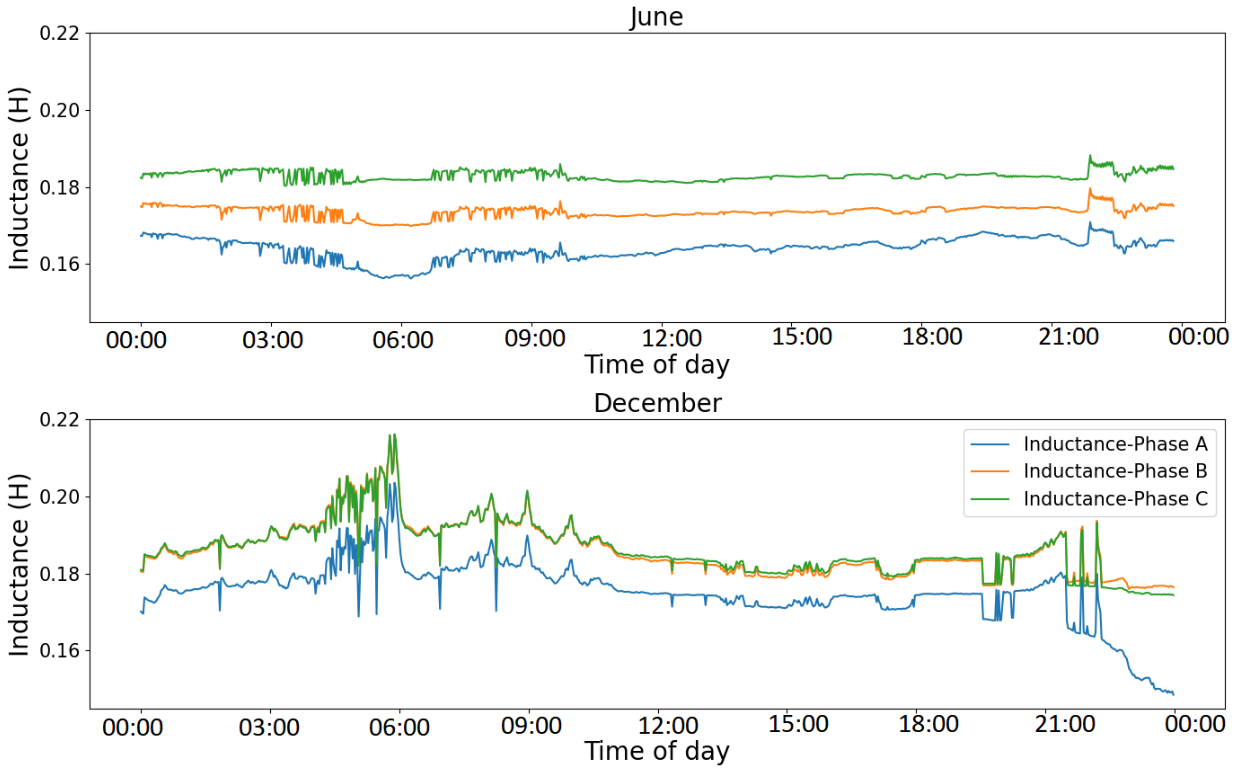

Figure 9: Inductance estimates obtained for Line B. The x-axis indicates local time.

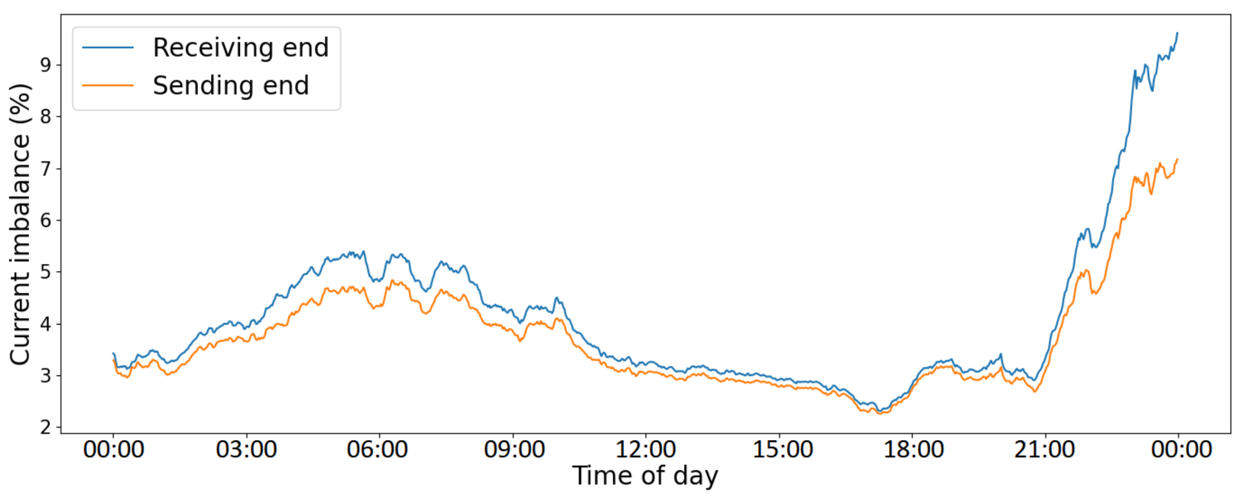

Figure 10: Current imbalance observed in Line B for the December day examined. The x-axis indicates local time.

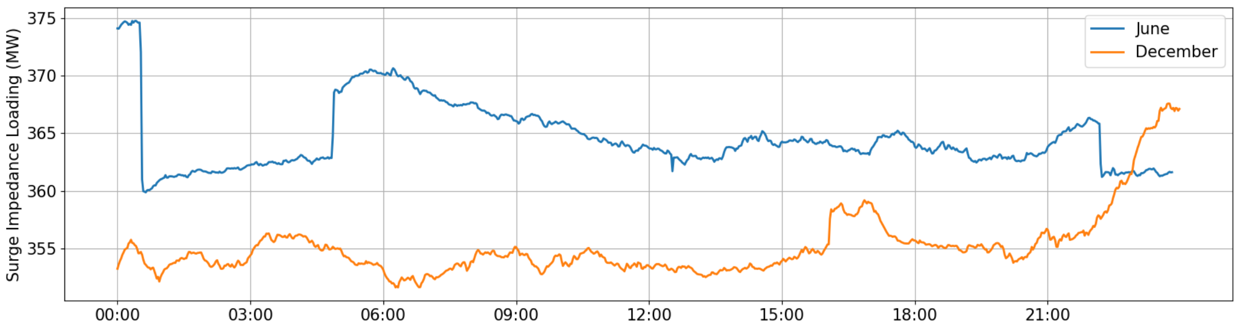

Figure 11: SIL estimates obtained for Line B. The x-axis indicates local time.

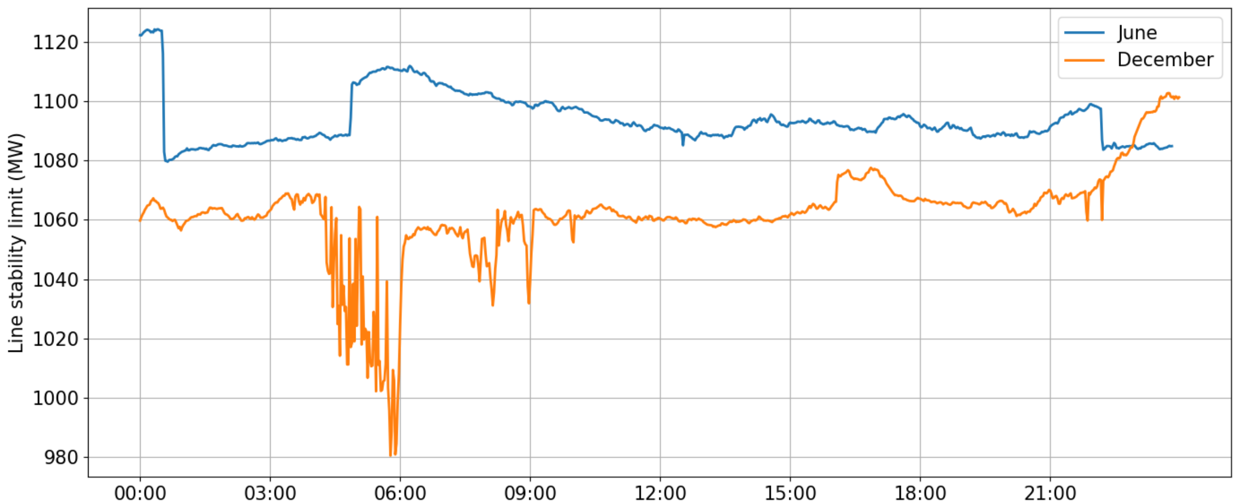

Figure 12: Line stability limits (loadability) observed for Line B. The x-axis indicates local time.

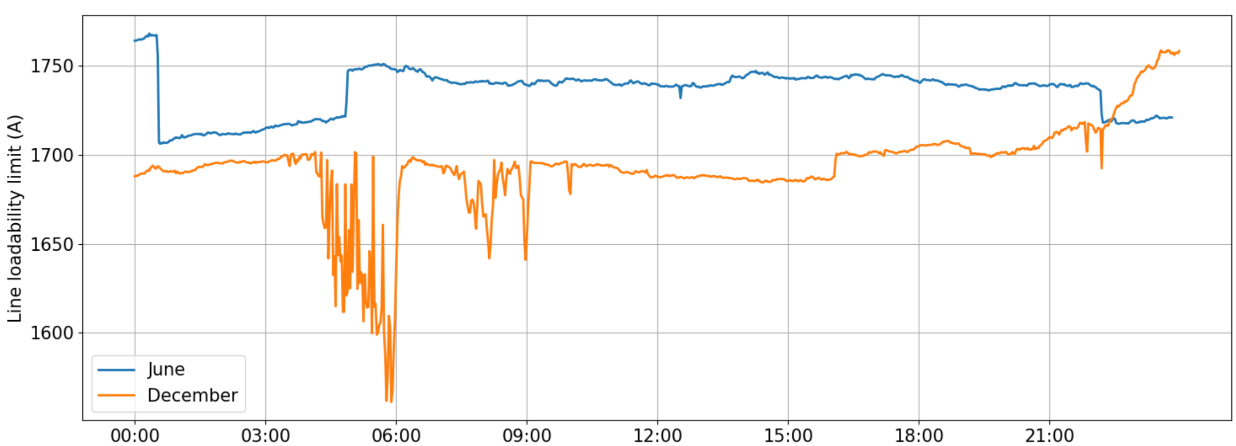

Figure 13: Line loadability estimates obtained for line B. The x-axis indicates local time.

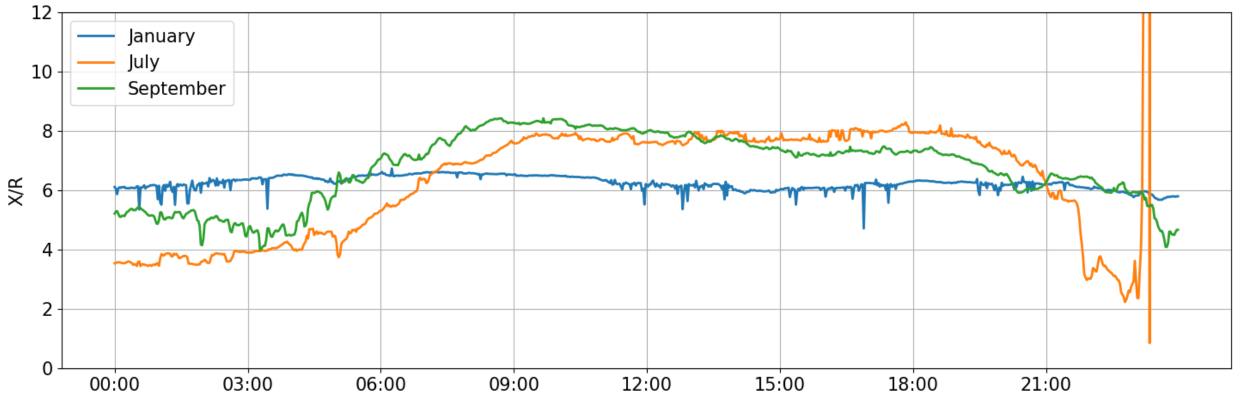

Figure 14: X/R estimates obtained for Line A. The x-axis indicates local time.

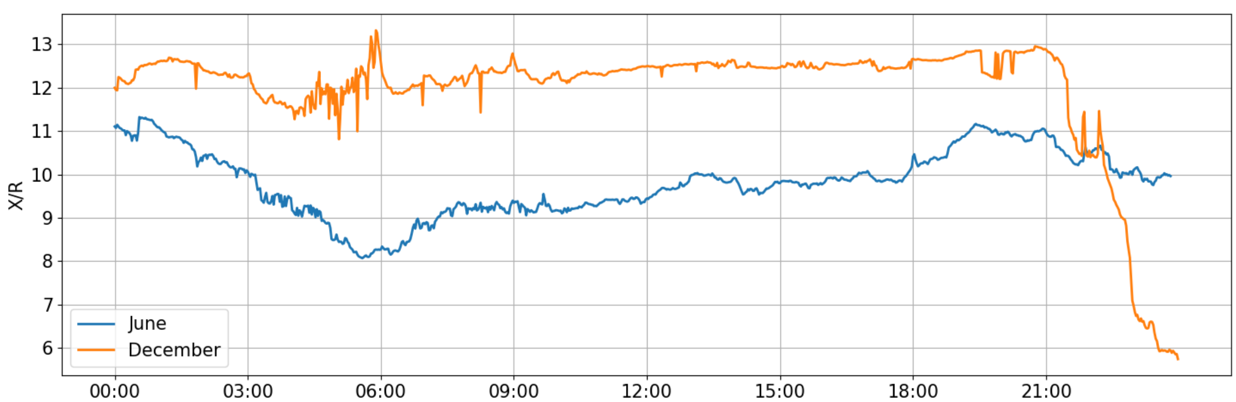

Figure 15: X/R estimates obtained for Line B. The x-axis indicates local time.

3.0 Conclusion

This report documents the findings from applying a blind research validation methodology to a commercial synchrophasor-based dynamic line rating software. In this study, PNNL researchers provided iterative feedback to Topolonet Corporation on the performance of their LineID^{TM} software when tested with PMU data from the National PMU Dataset [Banning et al., 2021]. Throughout this process, Topolonet leveraged the feedback to fine-tune their software, ensuring its robustness against data artifacts that may be encountered in field deployments.

This exercise also demonstrated that the NPDS can continue to benefit researchers despite the existing limitations that prevent data from being shared outside PNNL. The authors may pursue additional avenues where a similar blind validation approach can help test the robustness of solutions at medium technology readiness levels.

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