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Enhancing Grid Reliability with Large-Scale Sensorless Transmission Line Monitoring – Case Study: A Year on the Line

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SUMMARY

Transmission system operators face many challenges managing their power line assets. Supplying an essential service to consumers, the transmission line network extends over vast distances and is exposed to the elements. Therefore, transmission System Operators (TSOs) must monitor and inspect their powerlines to maintain the service level and grid reliability.

Existing monitoring technologies offer limited solutions. Scale is a major issue with all visual inspection methodologies, even if these are automated via drones, for example. With the vast area of a transmission grid, such inspections are limited to a few annual visits in a best-case scenario. While sensors installed directly on conductors or towers provide good indications, the network scale means that deployment for long transmission line segments is cumbersome and expensive and does not provide a solution that can span miles. In addition, substation-based monitoring technologies are limited and do not provide the necessary data resolution to detect and report all anomalies that threaten the grid's integrity.

With the growing shift to renewable energy sources, there is a higher dependence on the transmission network. Energy is generated where it is available and needs to be transported across vast areas. The need for large-scale grid monitoring is stronger than ever.
The last few winters and several intense storms have demonstrated this need as operators struggled to locate where faults occurred to restore service. A fully distributed monitoring method, which monitors powerlines for miles and more at all times, and weather conditions can provide the needed solution.

This paper will share a novel large-scale powerline monitoring method. Using optical fiber sensing, it will demonstrate a new approach to monitoring for miles with complete grid coverage at all times and conditions. Using an existing OPGW cable, the internal optical fiber becomes a highly sensitive sensor for the length of the cable. Thus, it demonstrates a truly distributed monitoring method without installing anything on the wire. In order to fully cover parts of the network, no extra sensors are added to the transmission infrastructure, and monitoring can scale and cover hundreds of transmission miles. A monitoring solution that is

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also continuous, constantly measuring and capturing fast-occurring events as they happen (such as partial discharges) and long-term deterioration, which accumulates over time and can lead to flashovers

One such system is installed at a north American TSO, monitoring tens of miles of a 345 kV overhead transmission line. For over a year, we monitored real-time and recorded data continuously. The detailed data was cross-referenced with external data sets such as temperature, humidity, winds, lightning strikes, ice storms, and precipitation. We demonstrate a strong correlation with the localization of events down to tower location. Our data points out specific tower locations which show higher partial discharge and corona buildup over time – affording a TSO an opportunity to perform preventative maintenance by washing or replacing problematic insulators. Wind strength is calculated along the overhead powerlines, and cable tension correlates with icing and possible lightning strikes near towers. More than a year's data, captured through the different seasons and changing conditions, holds further information that can be analyzed to include more physical and electrical abnormalities.

We will show that a monitoring solution such as this enhances the grid's reliability and resilience. With distributed and continuous monitoring, TSOs can start reducing maintenance costs as events are reported with accurate location and in real-time. Moreover, developing phenomena, such as Corona, which may lead to partial discharges, can be alerted in advance, allowing for preventive action.

KEYWORDS

Grid Enhancing, Grid Reliability, Fiber Sensing, Transmission Monitoring, Overhead Powerline Monitoring, Asset Management, Preventive Maintenance, Case Study, Digital Transformation

The challenges of grid monitoring

The electric grid serves billions of homes, businesses, and facilities worldwide. It is an ever-growing complex network with a transmission backbone, feeding energy from power plants and renewable energy resources to distribution centers and consumers. It is essential to our daily lives and yet is perceived as something which is always there, in the background, ever providing and working. It is a transparent, almost taken-for-granted service until it stops working. Once the service stops, it disrupts people's lives in ways ranging from annoying to life-threatening.

Such an intricate system can fail in many ways and places, but the transmission grid is a vulnerable part of this complex network. Transmission lines cover very long distances. In the U.S. alone, there are 600,000 miles of transmission lines[2], most stretching in rural and hard-to-reach areas. As a result, knowing that a fault occurs and locating it becomes a challenge. For example, when Hurricane Ida hit Louisiana in 2021, it damaged 208 power lines belonging to Entergy, whose transmission system spans land, water, and marsh. The inspection stage alone took several days. The process of finding out where faults were and heading out to repair them took a long time and effort, as many felled poles were in hard-to-get areas.

The above example demonstrates one of the significant challenges TSOs face as they move forward with upgrading their transmission grids on the path to better reliability. The sheer scale of the transmission grid makes inspection a task of herculean effort. The ability to identify a fault as soon as it happens and as close as possible to the actual location of the event is why grid monitoring is one of the building blocks of the future smart grid. Monitoring the grid at all times is key to grid reliability. Better insights on the grid gained by monitoring open the door to predicting faults before they happen, allowing for preventive maintenance.

Grid monitoring technologies today

Grid monitoring and inspection are not new ideas. Many operators use different means to watch over and manage their transmission assets combining multiple abilities to gain insights into their system.

Traditionally, there are electrical monitoring capabilities in high and medium voltage stations feeding the grid. Fault recorders allow for the detection of electrical faults. However, they do not deliver the needed insights for a modernized grid; do not provide accurate location for repair teams; and are limited to a short class of faults.

Another standard inspection methods are visual inspections. Many TSOs deploy fixed cameras monitoring lines with thermal, Corona, LiDAR, or regular photographic sensors. Line and tower survey methods use similar cameras mounted on drones, helicopters, or any other type of UAV flying above or near a line. Ground patrols - inspectors visually scanning powerline segments – are still a common and valuable method to inspect powerlines.

All these methods share a downfall – the scale of the network and the low monitoring frequency (derived from the grid size).

Any mounted camera can only scan a limited part of the grid, even on a fast-moving helicopter. Without any discussion on the price of flight hours which is also a hindering factor, even helicopters can cover a limited powerline length per day. Moreover, the large span of the power grid means that it will be scanned once a year or less. Such low inspection frequencies limit any preventive maintenance goals.

There are also weather limitations as helicopters, drones, and even line people can't be out in bad weather. Time of day limitations further narrows the amount of inspection time. When dealing with phenomena such as partial discharge and Corona buildup, the best time to observe it is about dawn when air humidity is high. During the day, when the sun dries the air, there will be lower traces of the buildup. Again, the ability to predict and prevent partial discharges and even flashovers is impacted.

Recently, new sensing technologies are being used with the push for better modernization and digital transformation of the grid. Sensors are installed directly and clipped on conductors to provide mechanical detection and temperature measurements. Others are being installed on power towers to provide similar indications. These types of direct install sensors offer accurate data and great localization – reporting on the spot they are deployed and doing so in any weather. However, scale is a limiting factor again. Any of these sensor technologies are placed on a conductor line or tower and can't report on the state of the next tower or any other segments nearby. It is a localized solution that does not scale. Deploying it on a larger scale is cumbersome and expensive work that introduces operative challenges to maintain such an array.

The scale of the modern grid is what makes it unique. It is one of the most complex machines the modern age has built. It is becoming more extensive, flexible, intricate, and dependent upon as we look ahead to the future grid with the growth of renewable energy sources.

As a monitoring technology that fits the needs of this future grid and modern TSOs, we propose a different distributed solution that scales easily while being continuous and constantly on the lookout.

Distributed optical fiber sensing

Distributed fiber optic sensing measure and monitor different activities along the entire length of an optical fiber. The physical fiber can be used as a highly sensitive sensor for its whole length, spanning tens of miles or more.

The underlying technology relies on a physical phenomenon called Rayleigh-backscattering. When light travels through an optical fiber, a minute fraction of the light is reflected back toward the light-emitting source. This effect is related to microscopic imperfections in the fiber material, the silica from which the optical fiber is made.

An optical unit transmits laser pulses into the optical fiber, receiving the back-reflections. The reflections change when physical events occur near an optical fiber that applies pressure, strain, temperature change, or acoustic waves hitting the fiber. The change is evaluated and translated to classify and identify what type of event caused it. The location or the distance to the causing event is calculated from the time between light transmission until a specific back reflection is captured. Since the speed of light traveling in an optical fiber is known, the time

difference can be translated to distance (with adjustments as the optical fiber may leave the powerlines, for instance, at substations).
This passive method does not require any amplification or power sources along the fiber. While several distributed fiber sensing methods exist, we limit the discussion to using Distributed Acoustic Sensing (DAS) in this article. Distributed Acoustic Sensing is a fiber sensing method that converts the back reflections of the transmitted light into an acoustic signal.

Fiber sensing applied to powerline monitoring

Fiber sensing has been used in the oil & gas industry and secured perimeter defense for years. The optical fiber is buried in the ground in all of these cases. In underground scenarios, the fiber is deployed near the infrastructure, so the two share the same stimuli. Distributed Acoustic Sensing relies on mechanical vibrations, thermal energy, and acoustic signals, which affect the fiber and travel well in the ground.

When used in an overhead powerline scenario (as part of the optical ground wire cable), many different stimuli (winds, environmental noises, weather conditions, etc.) interfere, making sensing much more difficult. The signal-to-noise (SNR) ratio in such deployments is relatively low, making it harder to isolate and identify the actual events.

Figure 1 depicts the data collected from a buried optical fiber in a waterfall-type plot showing the strain induced into the optical fiber vs. location and time The blue and yellow correspond to shrinking and expansion of the optical fiber. In Figure 1closer to the 9000m mark from the interrogator unit at a substation). In Figure 1, there is a minute vibration near the 9000m mark caused by external stimuli near the fiber, such as an engine running on top of the buried cable. While most of the background is free of artifacts, it is easy to identify a pattern that changes over time and distance. The ground, in this case, attenuates the noise and allows for better sensing.

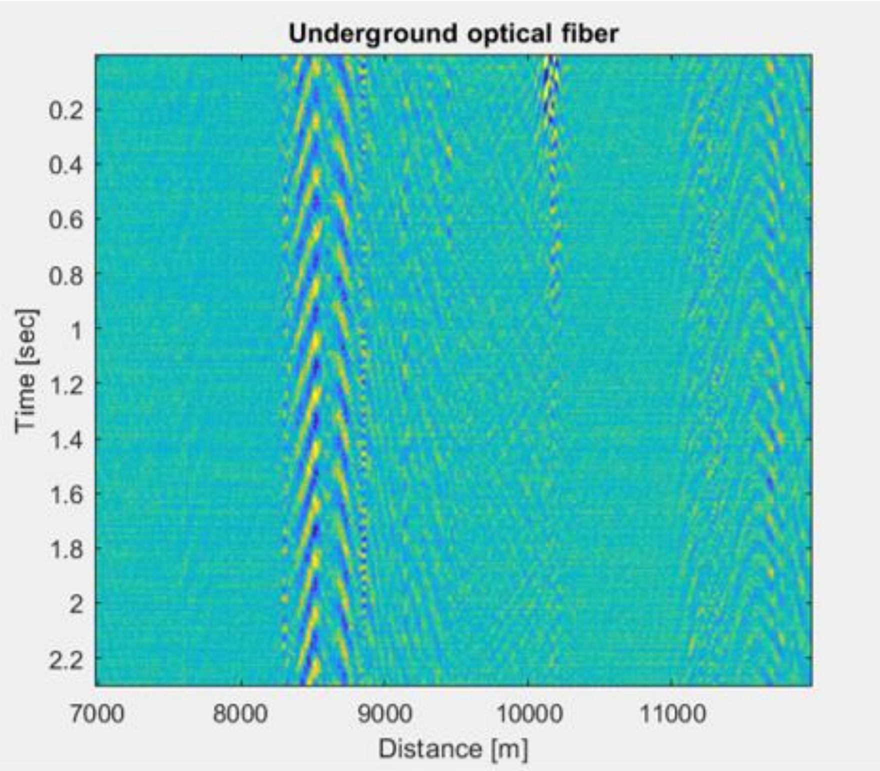

Figure 1 - Buried Optical Fiber Signal

The difference is striking when compared to a similar waterfall plot (Figure 2) depicting the same input taken from an overhead powerline equipped with an OPGW. There are no distinct patterns, and the vibrations of the optical fiber that are so clear in Figure 1 seem almost chaotic.

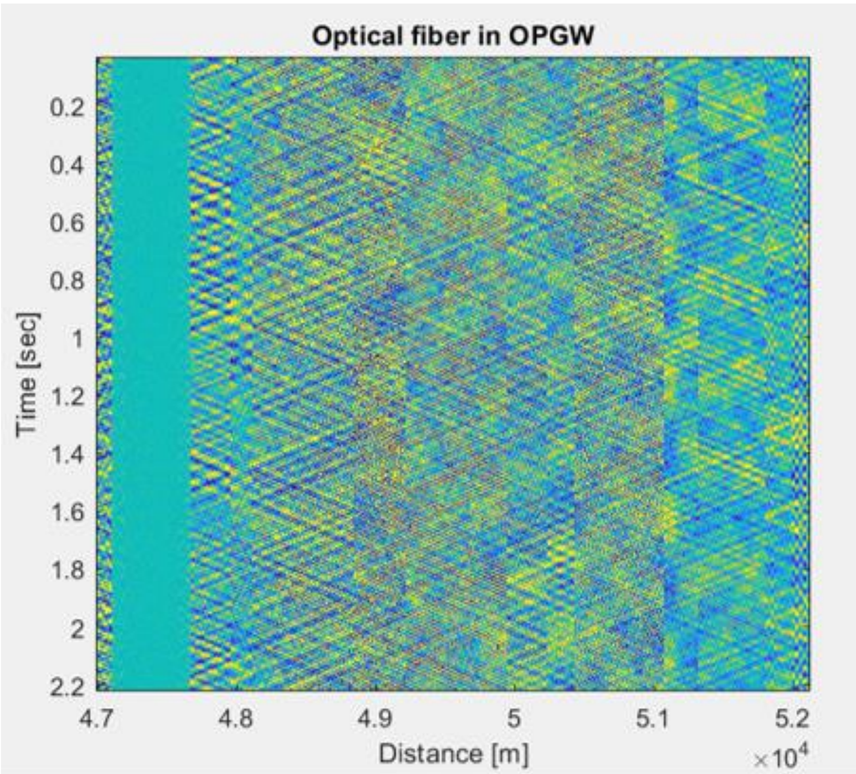

Figure 2 - Optical fiber in a free-hanging OPGW

The plot looks noisy. The data constantly changes over a short period of time because the cable is hanging free and can move in any direction with small wind bursts, making it hard to single out events of interest. The interesting events are lost in the vast uninteresting events. Even a minor factor, such as the sun hiding behind a cloud, will change the data read from the fiber as there is a sudden temperature drop.

Comparing these two figures shows why optical fiber sensing is prevalent in scenarios where the fiber is buried in the ground but never when the fiber is hanging free over tens of miles and more. However, the benefits of fiber sensing make the goal of applying it on overhead powerlines much more worthwhile

Benefits of optical fiber sensing for overhead lines

Using optical fiber sensing to monitor the grid holds several significant benefits. First and foremost, it is the scale issue. Fiber sensing can scale and cover the grid wherever there is an optical fiber, as part of the OPGW and, in other cases, retrofitted, wrapped on conductors (several such commercial solutions exist, such as AFL SkyWrap). Wherever the fiber is deployed, it can be monitored – for hundreds and even thousands of miles.

Deployment of such a fiber sensing solution is simple. It connects to an unused fiber (a dark fiber) where the optical fiber leaves the overhead wires, mostly in substations. In other cases, the optical fiber drops to ground level using MUFA closures in locations where communication equipment exists. Fiber sensing uses a single dark fiber leaving the rest of the fibers in the OPGW untouched.

Using DAS, every part of the fiber itself is the sensor. Since it can scale to cover any grid segment with fiber installed, it is a truly distributed monitoring solution that can grow to grid sizes.

Compared to any of the patrolling methods mentioned above, fiber sensing of powerlines is a continuous method. It inspects and monitors continuously, 24 hours a day and seven days a week. It will monitor during the day and night, during any weather condition. Even in harsh conditions when no flying patrol can inspect, fiber sensing continues.

Introducing PrismaPower

PrismaPoweris Prisma Photonics' solution for power grid monitoring. It is based on the proprietary Prisma Photonics Hyper-Scantechnology, which captures a very high level of data from the fiber. The detail is high enough to bring the signal-to-noise ratio to a high level to produce insights even in cases such as the overhead powerline, as depicted in Figure 2. It is a combination of advancements in fiber sensing technology allowing for greater detail, higher monitoring distance (each unit can cover over 120 miles from a substation), and machine learning algorithms that can detect anomalies in the detailed data. This combination, for instance, allows PrismaPower to detect the location of the power towers without reaching out to the towers themselves or installing anything on them.

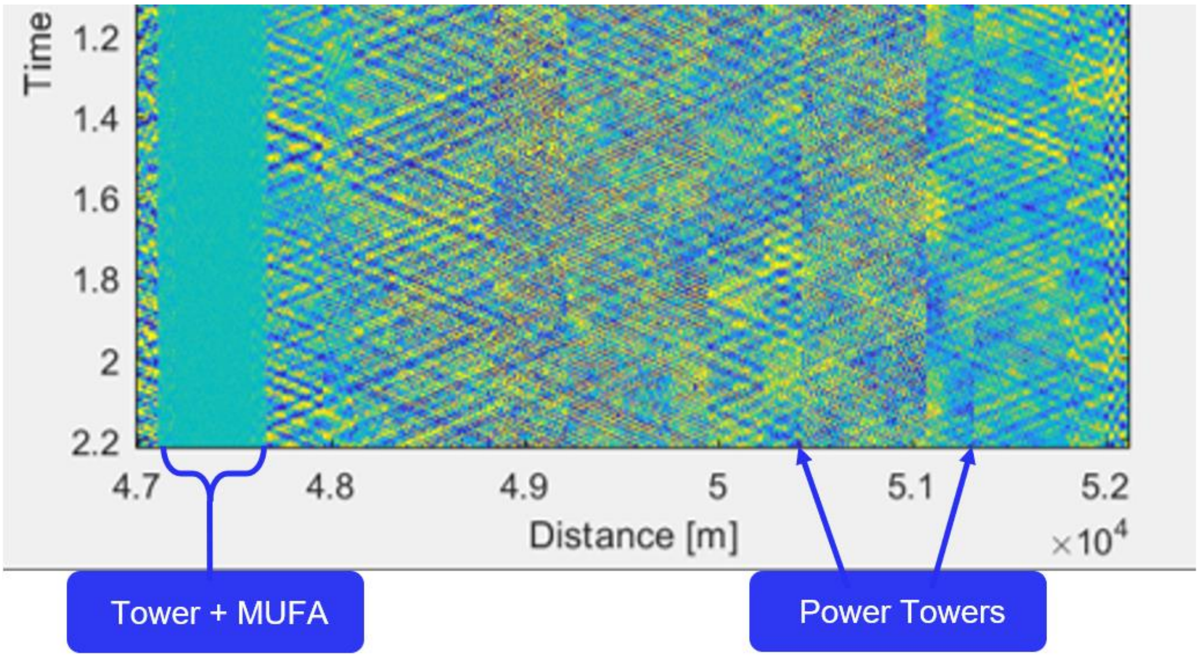

Figure 3 - Detail from OPGW monitoring

Figure 3 shows a detail from the overhead line monitoring waterfall plot depicted in Figure 2. The level of detail that PrismaPower captures allows it to see subtle changes in the patterns. As these reflect the movement of the cables, the points where the patterns break and change (seen on the right, with arrows) typically correlate to the location of power towers. On each side of the tower, cables swing slightly differently because of wind change, strain, tension, and many other factors. Another insight is shown on the left side of Figure 3. This empty, quiet space is the MUFA enclosure, where the optical fiber is coiled and shielded from external stimuli. Again, the detail and translation of this data into real-world locations allow for PrismaPower to pinpoint events in specific tower locations.

PrismaPower is deployed in the field, with several TSOs worldwide, including IEC in Israel and NYPA in the U.S.

A year of monitoring – putting it to the test

More than a year ago, we installed a PrismaPower system in a substation, monitoring a U.S.-based 35-mile section of a 345 kV powerline. The system was set up to capture and store raw data to gain long-term insights. As the raw data sets are enormous, PrismaPower was monitoring in real-time, but only 2 minutes of raw data were saved for each hour of the day. This was done every hour for 24 hours a day and 7 days a week. So the monitoring activity continued for almost 18 months – recording data on a 35-mile powerline – hour by hour for analysis.

At the end of the year, we aggregated and analyzed the data. Then, it was cross-correlated with several external data sources, mainly containing weather data for that period. The external data included precipitation (rain and snow), wind data, temperature, humidity, and lightning strikes information. The weather data was hourly based, and the lightning data held the time of the strike, magnitude, and location, including distance from power towers.

We wanted to validate the monitored data with external data to demonstrate the accuracy and abilities of long-term monitoring. Specifically, we looked into partial discharges, measuring these continuously to point to locations that are more prone and may need maintenance. Wind measurements at a very local resolution, cable tension measurements, and lightning strike detection

Results – partial discharges monitoring

In general, the results showed a close correlation between the two data sets. Furthermore, the data gathered from the fiber matched closely with the data gained from external sources.

The first phenomenon we looked for was partial discharges. The goal was to compare the partial discharge reading from the optical fiber with humidity and temperature data. Partial discharges are closely related to air humidity, and as the graph in Figure 4 shows, we found a good following of the signals. Figure 4 shows measurements taken on the entire monitored line for a year. The partial discharge levels measured through the fiber are marked in orange, and the fit to humidity levels (blue) is better than the fit to temperature (dashed brown).

The correlation becomes much more evident when the signal strength is plotted vs. the time of day. In Figure 5, each point corresponds to the average signal strength over the entire year at a certain hour in the day (e.g., signal strength at 14:00 throughout the day). This correlates to the known fact that humidity is a key factor in the fluctuations of partial discharge levels throughout the day. In contrast, the monthly signal (Figure 4) strongly varies as humidity is not the only influencing factor. However, the averaged signal follows yearly and daily changes in humidity which is a key factor in the occurrence of partial discharge.

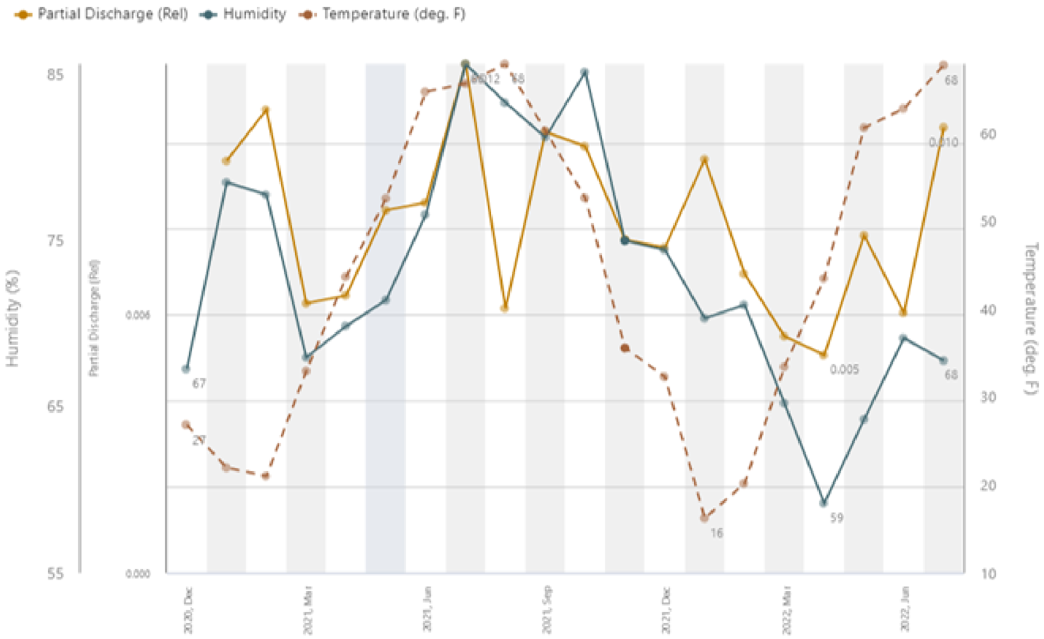

Figure 4 - Partial Discharge – Monthly Average

The resemblance of the two averaged graphs helps us demonstrate that the reading of partial discharges using fiber sensing is correct and closely relates to the actual status in the field.

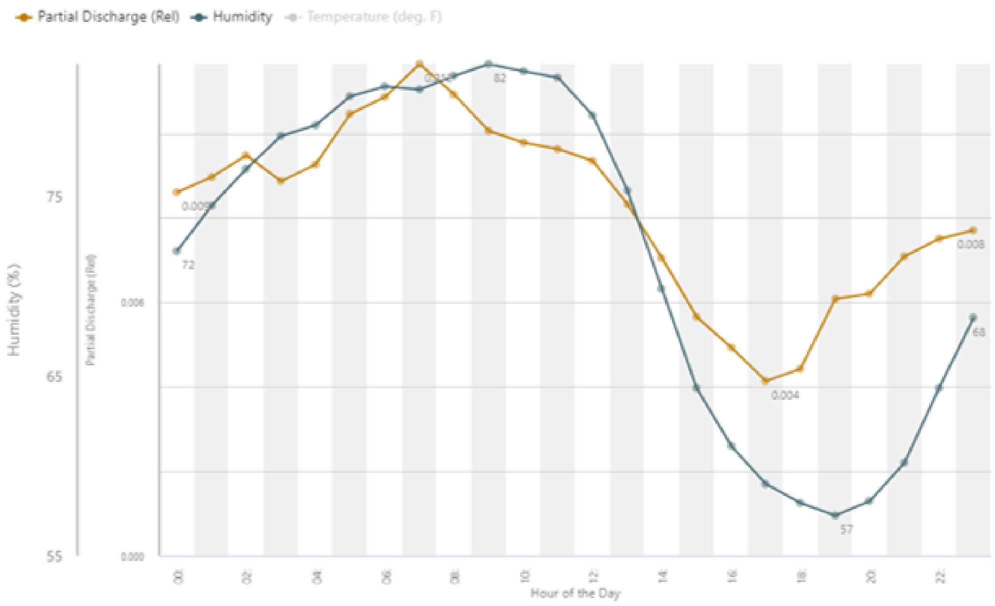

Figure 5 - Partial Discharge - Average Measurements

Next, we took a similar look at the entire monitored line, all 35 miles of it – searching for partial discharges. We wanted to show a correlation to the location of the towers, so we placed the average partial discharge readings on a map, shown in Figure 6. The Circle size corresponds to the average partial discharge signal of a given tower along the monitored overhead powerline.

There was an increase in the signal strength, hence increased partial discharge levels near substations (bigger circles in the middle of the line). Another observation is the high-level increase near open water (lakes and reservoirs), which makes sense as the air is far more humid around these water sources. The last observation can be viewed as large circles in the top right corner of Figure 6.

Figure 6 - Partial Discharge correlation to location

Continuing the partial discharge monitoring validation, we looked further to see what towers were more active. The monitored data has shown that some towers were 1,000 times more active than others. Moreover, the active ones may display a large variation over time, spiking even for a few minutes. Figure 7 depicts this fact – on the left, we see a measurement of partial discharges for three random days, monitoring several towers. After averaging many days on the same tower set, the right graph shows distinct differences. The low line tracks partial discharges on a specific tower throughout the day, and we can see very few fluctuations on what seems to be a low level of partial discharge. The top line shows greater values of partial discharge and a significant rise from 5 AM to 10 AM. This specific tower might require some maintenance to lower the damage potential.

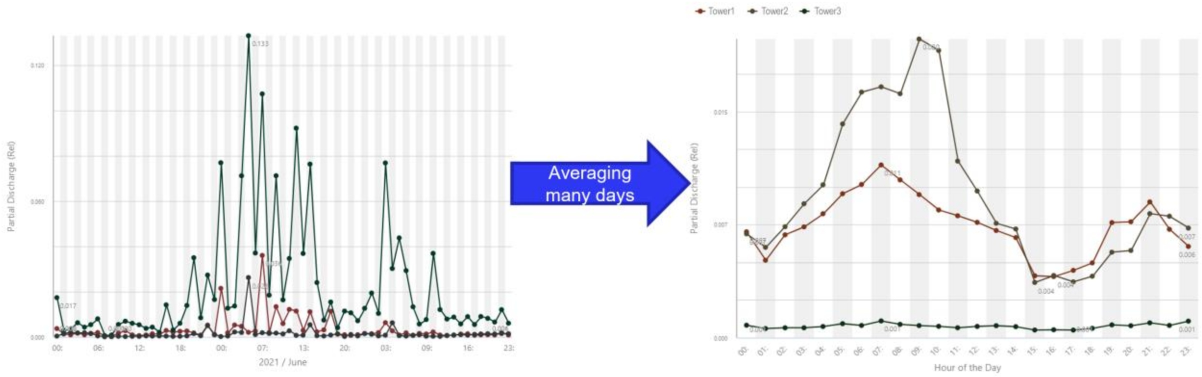

Figure 7 - Partial discharge and variation between towers and times

Comparing and finding those specific towers and getting partial discharge monitoring requires continuous measurement of all towers – throughout the day and night cycles. It is evident from these observations that distributed fiber sensing is a valuable tool for monitoring partial discharge levels on powerlines. By measuring continuously and not with sneak peeks by a passing patrol, long-term insights contribute to pointing out active towers, and preventive work can be carried out (cleaning insulators and replacing faulty parts).

More results – winter monitoring

Wind measurements are essential when discussing the weather and climate effects on overhead powerlines. Strong winds can lead to galloping and line faults and add loading stress on towers. Icing is also an issue, especially with strong winds, which can push on the formed icicles and start line galloping, increasing the forces on the cable to a dangerous level.

For that reason, we looked into distributed and continuous measurements of winds around the power lines. We also explored monitoring wire tension as means to detect icing. Again, using the same methods described above - looking at data collected over a year of optical fiber sensing and comparing it to an external data source – this time, examining wind data.

A strong correlation can be seen in Figure 8. The top and bottom lines depict wind speed gained from external weather report services. The top line, the red one, represents wind speed at 100m above the ground, while the bottom yellow one, is the wind speed at ground level. The middle blue lines depict measurements of slow vibrations of the OPGW. It clearly shows that the blue line closely follows the wind speeds over the entire measurement period, which was over a year.

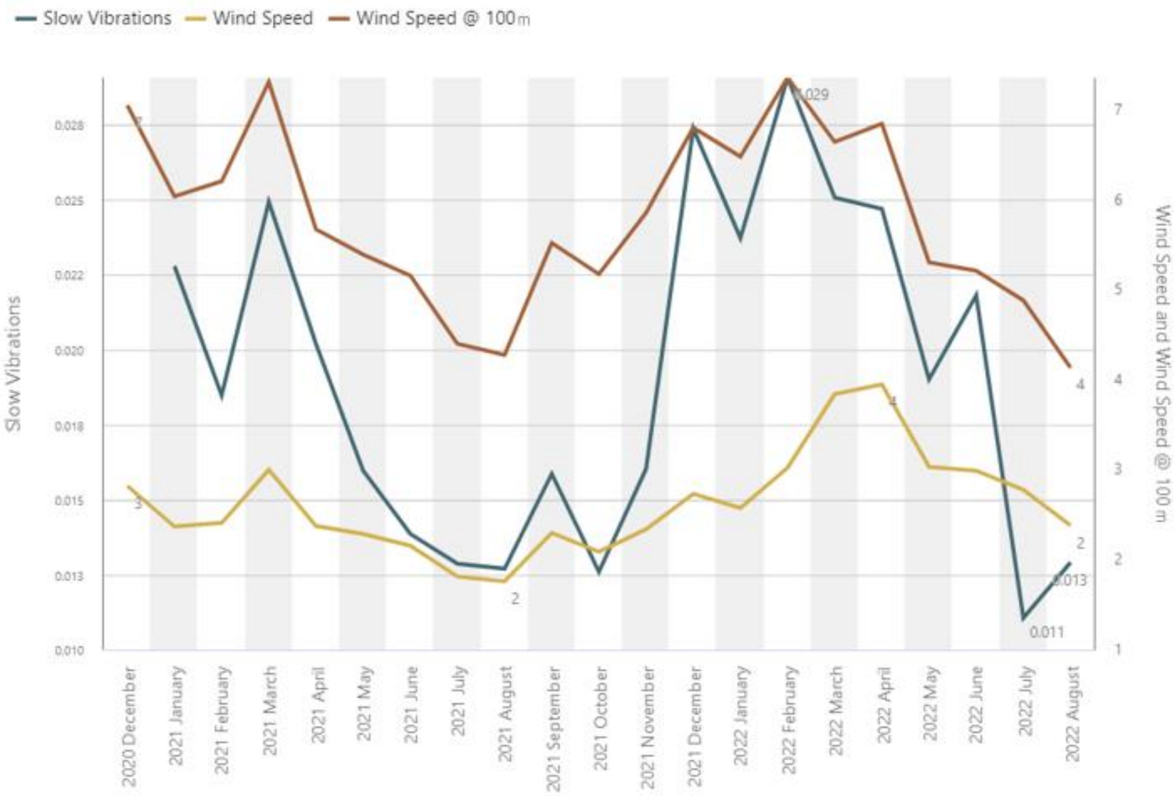

Figure 8 - Wind Correlation

A similar correlation can be seen when diving into daily level measurements and even hourly (Figure 9 and Figure 10, corresponding, using the same color key). The slight differences can be attributed to the fact that the fiber sensing measurements were distributed, using the OPGW as a sensor for miles and miles compared with external wind readings from meteorological sources that ignore micro-climate and topography factors. The ability to take correct wind measurements from the fiber itself and not general wind data collected and extrapolated by weather stations is robust. It opens up new possibilities beyond just wind measures – a new way to look at dynamic line ratings (DLR), for instance (more on that later).

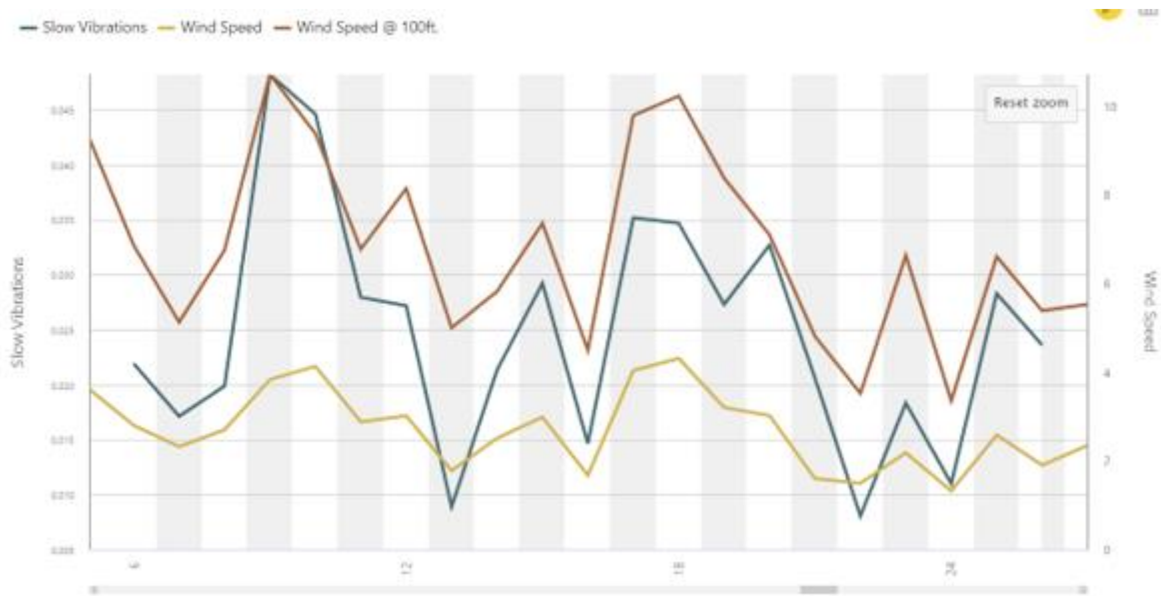

Figure 9 - Daily level wind correlation

Figure 10 - Hourly level wind correlation

Apart from wind speeds, the OPGW can be used to measure cable tension factoring in density dynamics applied to the fiber. Tension measurements allow for the addition of line icing detection capabilities. In February 2022, we saw an extreme dip in our tension measurements on the optical fiber in a specific area for a few days. We suspected that ice had formed on the line. To validate, we again correlated with weather data from an external source and compared it to our findings.

Figure 11 displays the correlated results. The red line (top) depicts changes in tension and density during the winter months and shows a substantial dip at the beginning of February 2022. That dip means that there is a significant variation in the cable tension and density, which suggests ice accrual. Weather data supports the icing proposition with intense precipitation before the dip (blue line) and no precipitation afterward accompanied by cold temperatures (yellow line in the middle) - a perfect storm.

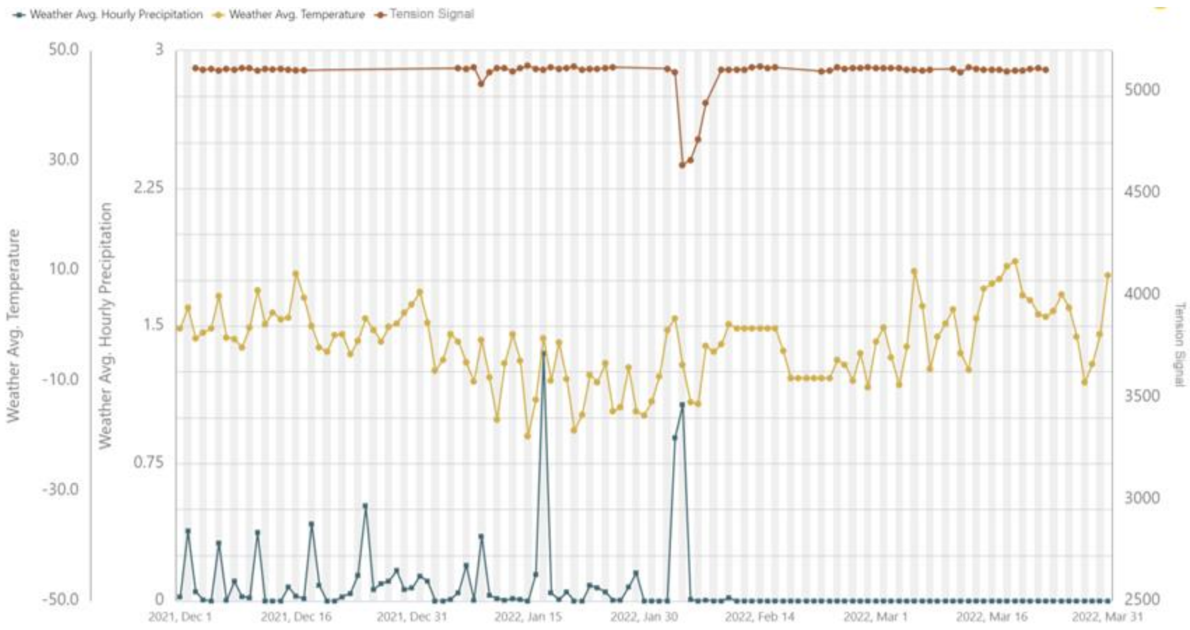

Figure 11 - Icing detected on the wire

Similar methods were used to detect lightning strikes with strong peaks in the measured signals, which correlated to lightning data from external sources. Matching the strong signal peaks to the locations of power towers (as calculated in Figure 3) gave us an option to report on lightning strikes close to specific power towers along the overhead powerline.

Grid reliability enhanced by rich real-time data

Regulators and TSO worldwide keep looking at ways to increase electric grid reliability to ensure that consumers have a dependable source of electricity to power homes, businesses, and all public services. Quoting U.S Federal Energy Regulatory Commission (FERC) chairman Rich Glick "The brutal cold during Winter Storm Uri last year, is a stark reminder that extreme weather remains a threat to the reliability of our energy infrastructure." [3]

Accurate measurements at the right time and with precise localization are vital to enhance grid reliability. It manifests itself in two ways – preventive and responsive.

Predicting where the troubles may emerge allows handling these before they become a threat to the grid. As shown above, the ability to point to locations where partial discharges are building up over a long period offers a more straightforward way to service specific towers. Such towers may have appeared perfectly fine during the yearly patrol. Moreover, knowing which powerline segments are prone to galloping gives operators a chance to implement reduction solutions locally.

A distributed way of monitoring is also effective in lowering costs. As fewer patrols are needed and less installation of additional sensors, fiber sensing can cover hundreds and more miles, sending line people to the right spot instead of constantly combing the grid.

Preventing faults before they occur is one way to enhance the grid's reliability. Accurate and timely response to disturbances and unexpected faults is another.

Rich real-time data from fiber sensing gives operators a chance to react immediately. It could be a local response, looking for physical damage from lightning strikes, downed lines (or torn optical fiber), or even vegetation hits on the lines. Wind information and icing give operators a chance for speedy and localized response and increase grid reliability and resilience.

Looking ahead

As demonstrated above, more benefits could be unlocked with large-scale, distributed, and continuous monitoring of power lines. In addition, more climate phenomena can be detected, such as wildfires which have an enormous impact on human life and the power network. Therefore, we expect to keep diving into the ongoing gathered data and validating its analysis with external resources.

Beyond grid reliability, there are network optimization issues, such as Dynamic Line Rating (DLR). For example, measuring wind and weather conditions directly off the power line in a distributed manner allows operators to optimize and introduce more capacity to transmission systems under peak demand conditions. The knowledge of the conditions in every grid segment allows for better optimization.

As operators are urged to modernize their grids, to meet increasing challenges, a monitoring method that can scale up to grid sizes gives them a powerful tool to address known and new transmission system conditions and better shape the grid of the future.

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