NON-CONTACT SENSOR SYSTEM FOR REAL-TIME HIGH-ACCURACY MONITORING OF OVERHEAD TRANSMISSION LINES

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ABSTRACT

Promethean Devices has developed, a non-invasive, low cost sensor system that delivers accurate real-time information on overhead transmission line clearance, temperature, phase current, and ampacity (maximum current carrying capability). The system is rugged, easily installed and calibrated in existing transmission Right-of-Ways, and is fully autonomous.

Since the method[2] senses the distribution of the AC magnetic fields to perform its measurement functions, it is inherently non-contact, thus scheduled outages, utility personnel, and utility field crews and equipment are not required for installation, calibration, and operational certification. Furthermore, operation and accuracy are not adversely affected by rain, ice, hail, smoke, dust, fog or snow. The sensors are buried under the right-of-way, protecting them from weather and vandalism.

INTRODUCTION

Background and Benefits of Real-Time Transmission Line Monitoring

Demand for electric power has grown significantly faster than the transmission system's ability to deliver it reliably. Since ~ 1989, growth in electricity demand has significantly outpaced growth in transmission capacity; as a result, the transmission grid is overburdened and is being operated in a manner for which it was not designed. System bottlenecks and congestion, blackouts, equipment damage, and system disturbances are becoming widespread and are occurring with increasing frequency, duration, magnitude and adverse effects, economic and otherwise. Congestion now costs electricity consumers > $ 4 billion/year; system disturbances (including blackouts) and power-quality issues cost U.S. businesses ~ $ 100 billion/year. Of the 5 largest US blackouts since 1965, 3 have occurred since 1996; the economic cost of the August 14th, 2003 Eastern Blackout was > $10 billion.

Real-time monitoring of critical, congested transmission circuits can improve reliability, relieve congestion, and safely permit more power to be moved over existing circuits than is presently allowable. As a result, the existing transmission system can serve greater demand, revenues and economic efficiency can be increased safely and reliably, and some significant demand-driven new construction and upgrade costs can be deferred for years. Simultaneously, system operational reliability and power transfer capability (transmission transfer capability) can be improved, and congestion-related

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[2] international patent application PCT/US07/77881

costs can be reduced. Promethean Devices' monitor addresses these needs and offers the above-mentioned benefits at moderate cost.

The Promethean Devices Real-Time Transmission Line Monitor (RT-TLM): Specifications and Performance Summary

Measurement	Accuracy, 99% confidence	Notes
Conductor height	+/- 0.12 meters	At ~18.5 meters.
Temperature	+/- 7 C	Temperature is derived from height.
Current	+/- 22 Amps	At 830 Amps, average.
Update rate	Every 10 seconds	
Data latency	< 60 seconds	More if network goes down; no data is lost.
Feature		
Measurement method	Non-contact AC magnetic field sensing.	
Ampacity estimation	Based on measured conductor temperature and ambient conditions, consistent with IEEE Std 738-1993.	
Power supply	Solar panel with battery backup.	
Communication	Wireless EVDO (cell-phone) network link.	

Table 1. Achieved performance of the Promethean Devices RT-TLM prototype. 99% confidence level accuracies were obtained by multiplying RMS uncertainties by 2.58 as described in the text.

The specifications in Table 1 reflect the capabilities of the present prototype as deployed under the Duke Energy Newport-Richmond 500 kV Tie, between towers 62 and 63. We will soon deploy a second generation system that will have similar performance, at significantly lower power consumption.

Potential System Capabilities: Conductor Oscillation Amplitude & Frequency, Wind Loading: Conductors and Towers, Ice Detection and Monitoring, and Conductor Galloping,

In principle, the AC magnetic field provides real-time information on the positions in space of each overhead conductor. As the electronics and software of the Promethean system improve, we expect to provide information on "fast" events such as conductor movement due to wind and galloping. The present system provides sag averaged over the three conductors, as needed to monitor thermal expansion, but with some refinements, it could also give information on uneven loading such as in the case of ice and/or mechanical failures.

APPARATUS

The Promethean RT-TLM consists of a field system that senses power line status and a base station that performs analysis and provides a real-time web-based information display. The field system is linked to the base station by a wireless network. As sketched in figure 1, the field portion of the RT-TLM has three sensors positioned at or below ground level and these are linked to an electronics package that handles data reduction and transmission to the base station.

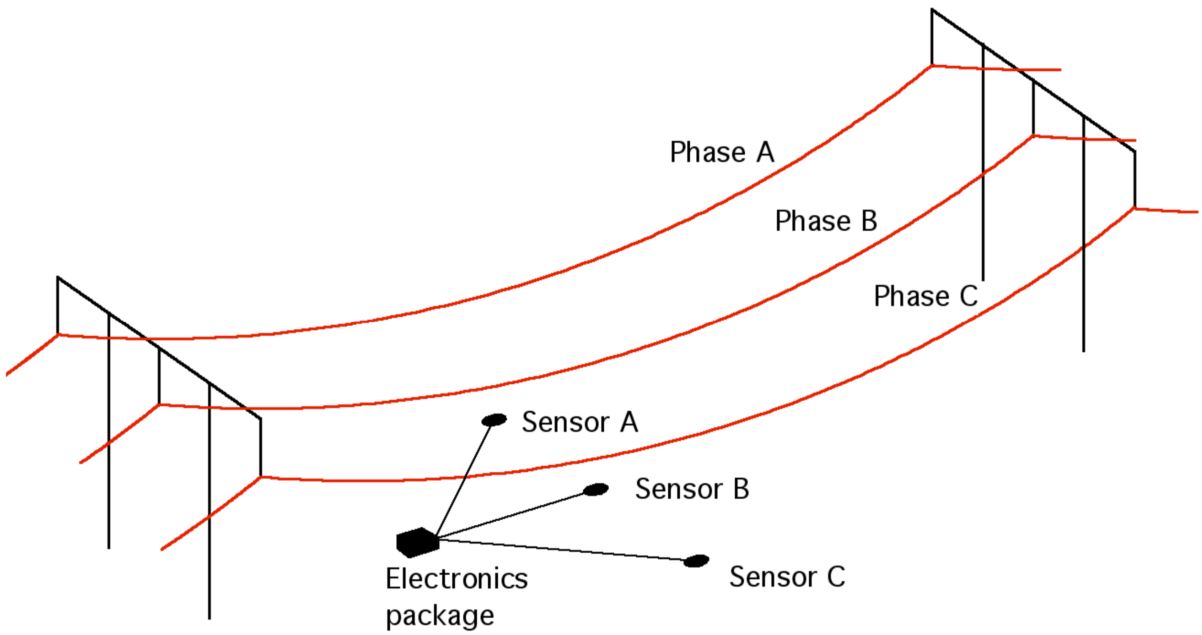

Figure 1. Overview of the Promethean Devices Real-Time Transmission Line Monitor (RT-TLM). For permanent installation, the electronics package and sensors are underground.

Sensors

The sensors consist of a pair of coils, orthogonally oriented and are located approximately under each phase conductor, as shown in figures 2 and 3. For protection from weather and vandalism, the sensors are buried. Although the sensor positions are not critical for system operation, their precise locations must be known for later calibration.

For ease of installation, a second generation sensor, shown in figure 4, has been developed that will be more easily installed.

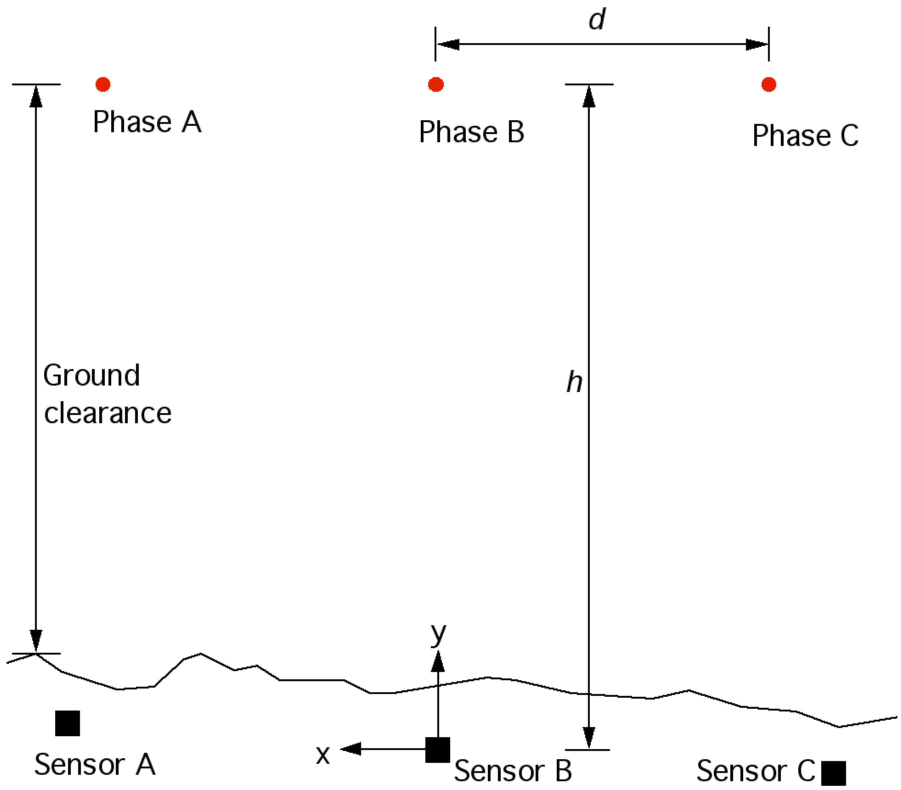

Figure 2. Cross-section showing three transmission line conductors, and the below-ground placement of the sensors. Note that the positions of the sensors need not be specified to great accuracy, but an accurate survey of the "as-installed" sensor locations is needed for calibration.

Figure 3. Installation of prototype sensor. Sensor consists of two orthogonal coils, visible as white spools mounted in the plastic framework. Second photo shows the B (middle) sensor vault. The C sensor's location is still apparent in the background as the grass has not yet covered the signal cable trench and vault.

Figure 4. Next-generation sensor that is smaller and easier to install.

Figure 5. Solar panel and prototype electronics package containing ADCs, a computer and a wireless data link. This will be replaced by a second-generation electronics package which will be installed underground, and will have much lower power consumption allowing the use of a smaller solar panel.

Electronics Package

The electronics package, shown in figure 5, contains two ADCs for each magnetic sensor, ambient temperature sensors, a ruggedized microcomputer for data reduction, and a wireless (cell phone) data link. The function of the computer is to convert the magnetic field waveforms to amplitudes and phases, and to send that information to the base station. If the network is down, the computer buffers the data and sends it when the data link is reestablished. The prototype system is powered by two 85 watt solar panels, with battery backup. A second generation electronics package will soon be ready that will consume a fraction of the power and will be buried. Only a smaller solar panel will be visible, so that the system will be as unobtrusive as possible.

Base Station and Information Display

The magnetic field phase and amplitude data from the field system is sent to a base-station at Promethean Devices' office. Alternatively, the base station could be in the customer utility's control center. The base station is a computer that analyses the sensor data and calculates the transmission line's clearance, phase currents, temperatures and from those data it estimates ampacity (maximum current carrying capability).

The resulting information is stored in a database and made available in real-time via a web interface, as shown in figure 6.

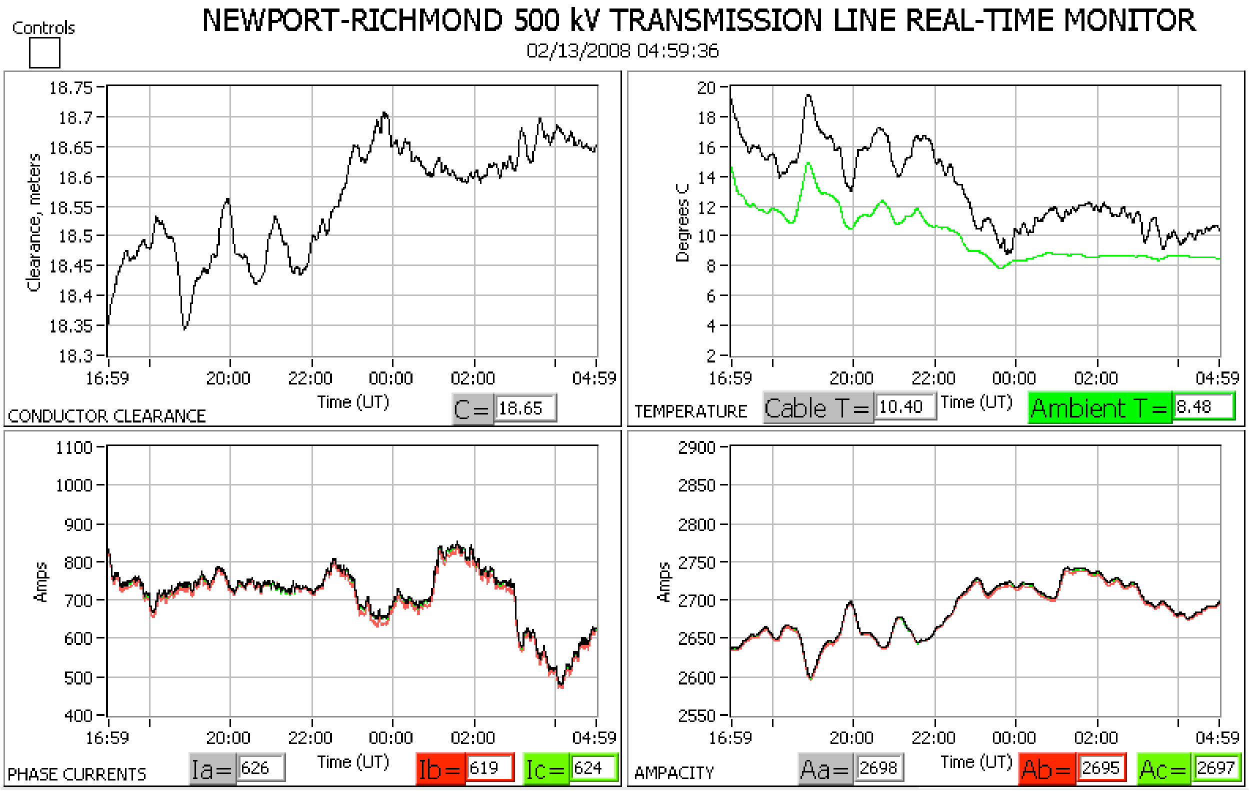

Figure 6. Screen shot of the prototype Promethean Devices Real-Time Transmission Line Monitor web display, showing conductor clearance, temperature, currents and ampacity.

Deployment and calibration

The steps for installation of a RT-TLM system are:

1. Identify a site under a transmission line of interest that is isolated by >100 meters from factors that would significantly perturb the magnetic field of the lines, such as roads and other power lines.

2. Excavate cavities for the sensors and electronics package and trenches for cables, and place the sensors.

3. Survey the sensor locations with respect to each other and the overhead lines.

4. Connect the electronics, the solar panel and take calibration data. The data will consist of "ordinary" magnetic field phase and amplitude data, but it will be augmented by laser range finder cable height data, and I.R. camera cable temperature data. About 10 hours of data is needed to calibrate and verify height tracking over a day/night temperature range.

5. At this point, the sensors and electronics can be covered with dirt. The calibration data is analyzed and incorporated into the base-station software.

6. System is now functional. Occasional return visits with the laser range-finder and I.R. camera will certify continued accuracy.

MEASUREMENT PRINCIPLE

Height and Current Measurement

The sensors in figure 2 each consist of an orthogonal pair of coils. One coil responds to horizontal, x-direction, magnetic fields while the other responds to vertical, y-direction fields. We have six coils, Ax, Ay, Bx, By, Cx and Cy.

Using simple electromagnetic theory:

1. Magnetic field vectors that are "slanted" can be broken down to x and y components. For example, a field that is at 45 degrees would excite a sensors x and y coils equally.

2. The magnetic field at a sensor is actually the sum of the fields from each phase. Each phase produces a circular field pattern as in figure 7.

3. Since the conductors have AC current, and each phase is 120 degrees apart, the three circular patterns are rapidly "turning on", then "off", then "on but reversed," and the pattern repeats 60 times per second. (50 in other parts of the world.)

4. The strength of the field from a given conductor at a particular sensor diminishes as 1/r, r being the distance from the conductor to the sensor. Hence if the clearance were to double, then the sensor signal amplitudes would approximately halve.

Based on these considerations, we can see that each sensor will see a different field strength and, although we haven't fully explained it, each sensor will see a field whose 60 Hz strength variation has a different phase.

To illustrate these ideas, consider sensor B's x and y coils. By examining figure 7, we see that the By coil is insensitive to the field from conductor phase B. That is because the (green) phase B field lines are horizontal at sensor B, and thus have no y component. Hence By will sense the superposition of fields from phases A and C only. The Bx coil, on the other hand, is sensitive to all three phases. Thus, by inspection we can predict that the Bx and By signals will have different amplitudes and phases.

In fact, under the ideal case of perfectly balanced currents in the three phases (i.e. no zero-sequence current) the ratio of signals By/Bx is equal to square-root of three times the ratio *h/d,* where *h* and *d* are the conductor height and conductor separations as indicated in figure 2*.* (Halverson, 2004)

The currents in the three conductors are usually unbalanced, causing a deviation from the simple ratio method of determining the height. For improved accuracy, information from sensors A and C is also used to determine the conductor heights, as well as the current in each conductor.

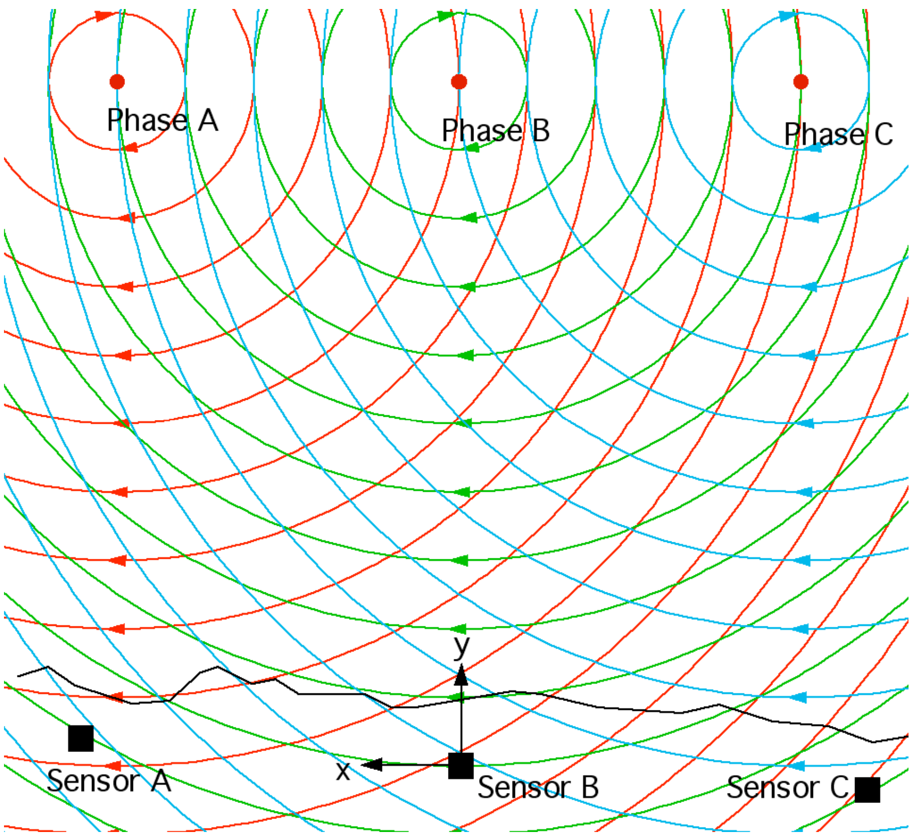

Figure 7. Magnetic field lines from conductor phases A (in red), B (in green) and C (in blue.)

<u>**Algorithm**</u>

The electronics package records the sinusoidal waveforms from the six coils and begins the height and current determination process by filtering out high-frequency noise and determining the magnitude and phase of each signal.

The next step uses an electromagnetic model of the three conductors. The model calculates the magnetic field amplitudes and phases that *would* be measured *if* the height *h* and the overhead conductor currents *Ia, Ib* and *Ic* were to be at some initial start values. An iterative fitter program adjusts the values to minimize the error between the predicted and measured magnetic field signals. The final iteration is the "answer," our best value for actual height and currents.

Height and Current Calibration and Error Sources

Once the sensors have been installed under the power lines and initial RT-TLM data has been acquired, it is necessary to adjust the analysis software's height offset. This is done with information obtained with a laser range-finder (model ULS, from Laser Technology, Inc.) which is temporarily connected to the electronics package computer. Data is recorded continuously for ~10 hours to cover a range of temperatures and sags and the height offset is adjusted for optimal agreement between the RT-TLM and laser heights. Figure 8 shows the agreement obtained from the prototype system after the height offset has been set.

A similar calibration is performed for the currents. Current data (CT data) spanning the calibration run is obtained from utility CT records for the transmission line being monitored. That data may be used to adjust a scale factor in the software for optimal agreement. Figure 9 shows the agreement obtained after this procedure.

The magnetic fields from the overhead conductors are unaffected by precipitation and ground-cover, but care is needed in sensor placement to avoid obvious sources of spurious magnetic fields or field distortions. For example, the sensors should be placed at least 100 meters away from roads and other power lines.

Wind induced line sway may also introduce small changes in the line height. For the prototype sensor system, this appears as a small increase in the noise on the height signal. We are currently investigating changes to the sensor configuration that will allow us to detect and quantify wind sway. This will enable us to improve the height sensing accuracy and to provide wind sway data (wind loading) as an additional output.

Other "technical" errors, such as temperature induced drift in the electronics appear to be negligible but are nevertheless under investigation. At this time, the prototype has shown an apparent accuracy of ~5 cm in the height over 150 days of operation.

The error budget for height or clearance determination has two components:

1. The noise in the height determination contributes 2 cm RMS of uncertainty (see figure 8), more in high wind conditions.
2. The accuracy of the laser range finder contributes 4 cm.

Combining these in quadrature (taking the square root of the sum of the squares) gives an RMS uncertainty of 4.5 cm. We can scale this by 2.58 to get a 99% confidence level accuracy of +/- 11.5 cm. Under windy conditions, the height measurement will be noisier, ~3 cm RMS, so the overall height uncertainty would be 5.0 cm RMS, or 13 cm at the 99% confidence level.

At this time it is difficult to determine the sources of error in the current determination. The 8.4 ampere RMS disagreement between the prototype RT-TLM and the Duke current monitors (CTs) (figure 9) is larger than expected. It is possible that the error is not in the RT-TLM, but in the Duke monitors; our understanding is that the type of CT used has an accuracy of 2 to 3 %. Data gained in future deployments should resolve this question. At this time the overall accuracy of the current measurement cannot be independently verified. We will use the 8.4 ampere RMS disagreement as an initial estimate of the accuracy, subject to revision as new information becomes available. The 8.4 amp RMS scales to +/- 22 Amps at the 99% confidence level.

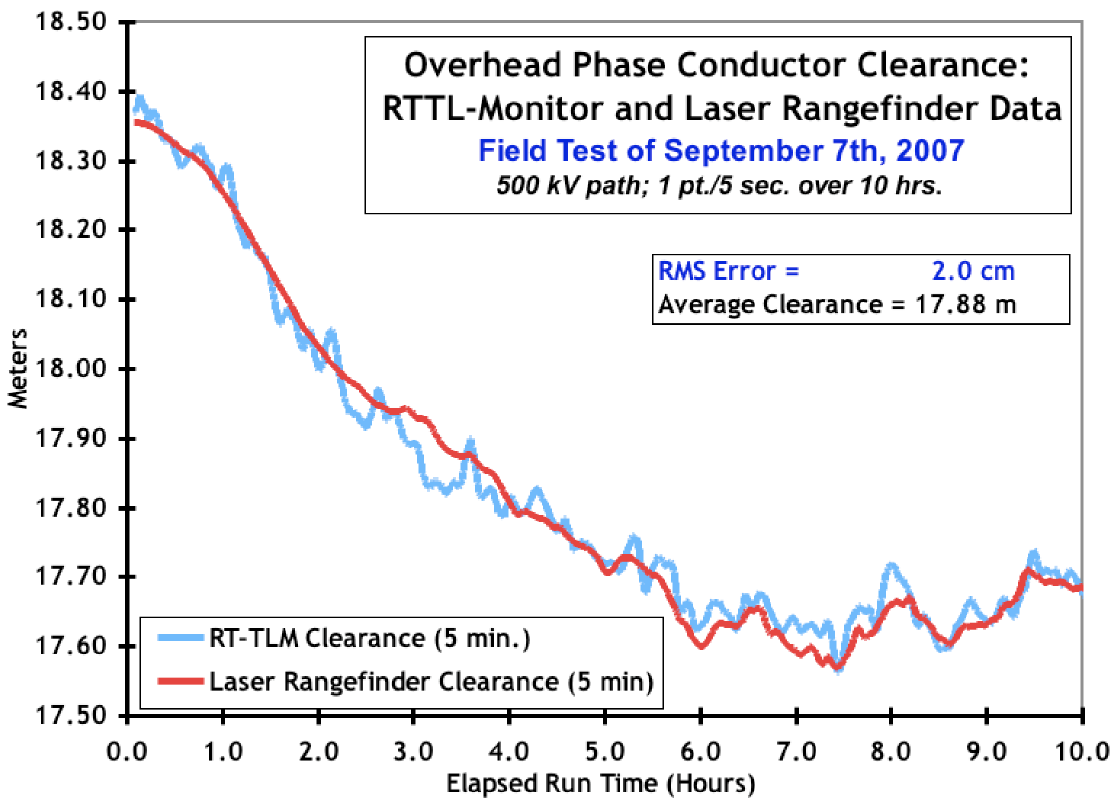

Figure 8. Conductor clearance measured by the Promethean RT-TLM, compared with a laser range finder. Data has been smoothed with a 5 minute window.

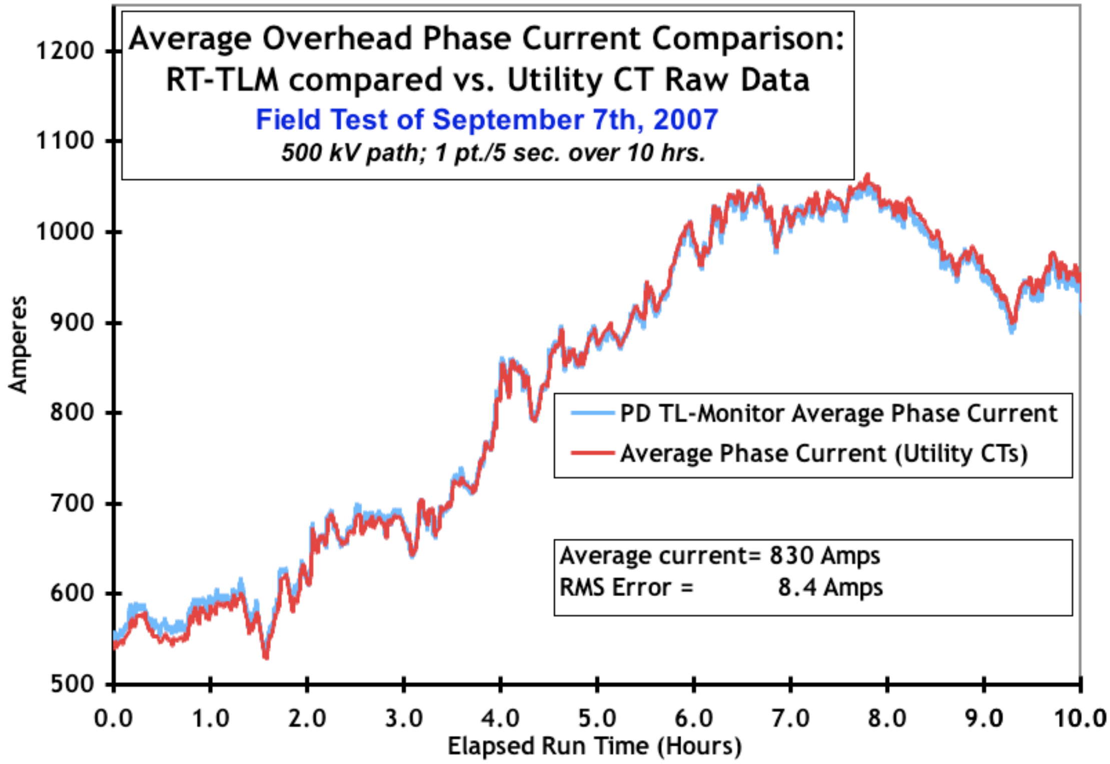

Figure 9. Current, average of three phases, as determined by the Promethean RT-TLM compared with real-time data provided by Duke Energy.

Temperature Determination

Because the thermal expansion properties of the overhead cables are well known, the height of the cables is a direct indication of their temperature. Hence, determination of the line temperature is straightforward: simply enter the height into a predetermined fit. Such a fit is shown in figure 10.

Temperature Calibration and Error Sources

To calibrate the RT-TLM derived conductor temperature, we directly measured the conductor temperature with an infra-red camera, FLIR Systems ThermaCAM EX-320, and we simultaneously measured the conductor height with a laser range-finder. This was done over a range of temperatures and the fit obtained in this manner, figure 10, gives us a height to temperature conversion.

There are three components to the conductor temperature error budget:

1. Noise in the height determination, as in figure 8. The 0.02 m height uncertainty is scaled by the conversion factor of -31.58 degrees per meter to give a 0.63 C error contribution.

2. Noise in the infrared data set, giving a 1.75 degree contribution.

3. The camera contributes +/- 2 degree C, as stated by the vendor.

Combining these in quadrature, we have an RMS uncertainty of +/- 2.7 C, which, for 99% confidence, scales to +/- 7 C.

We can improve the fit by collecting data over a wider range of temperatures. This will be necessary to account for non-linearities in the sag-temperature relationship as observed by (Hunt & Barret, 2006). The sag behavior of the line may also be calculated from the line sag catenary equations and the thermal expansion coefficients. This provides an independent way of validating the sag calibration and extending the calibration range outside of the measured IR camera range.

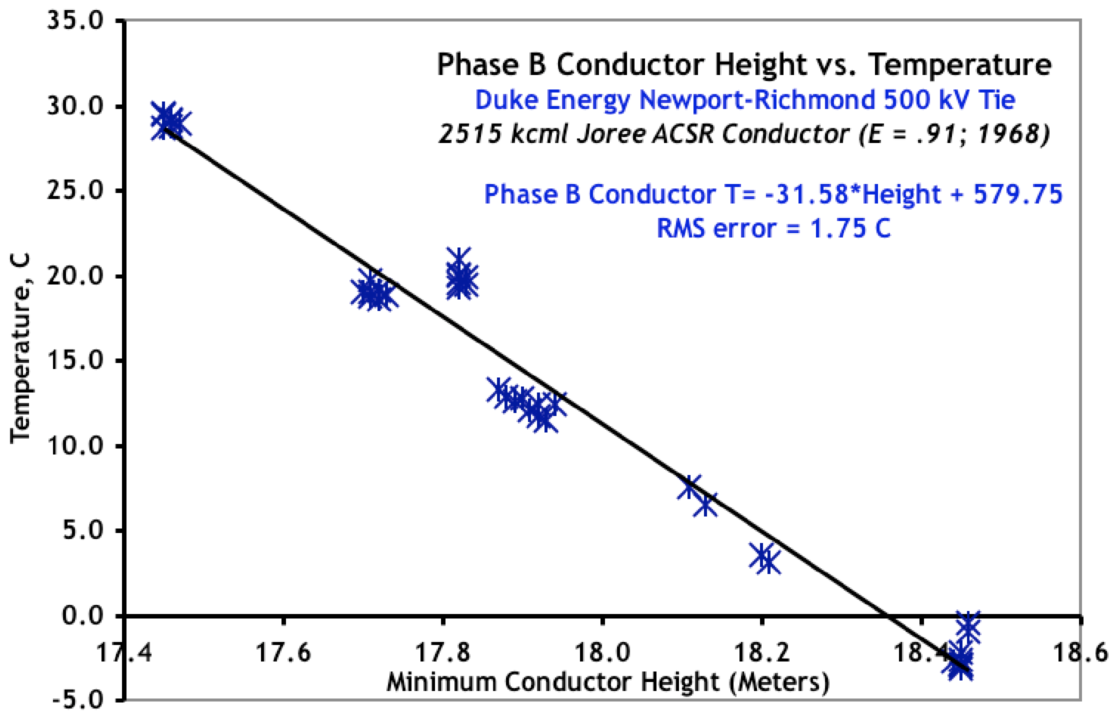

Figure 10. Laser-range-finder measured height versus temperature for the test site overhead conductor span. The linear fit serves as a height-to-temperature conversion and calibration.

Ampacity Determination

The present system measures both conductor temperature and the currents in each conductor. Additionally, the ambient temperature is measured by a sensor connected to the electronics package. These data, together with knowledge of the maximum temperature rating of the conductors provide enough information to estimate the ampacity, or maximum continuous current carrying capacity of the system. In computing the ampacity, we are answering the question "under existing conditions, how much current would heat the conductors to their rated temperature?"

The procedure for answering this question is outlined in IEEE Std 738-1993 which calculates ampacity based on conductor temperatures inferred from weather information, solar radiation and the physical properties of the cables. However our job is made much easier than the problem IEEE Std 738 solves because we *know* the conductor temperatures with reasonable accuracy and have to infer nothing.

From the conductor and ambient temperatures, we can easily compute the radiative heat flow into and out of the conductors. From the current, temperature and knowledge of the electrical properties of the cable we can compute the ohmic heating. Using formulas from IEEE Std 738 we estimate how much more heat is lost to convective cooling. Energy balance considerations then allow us to calculate an ampacity. This ampacity is plotted in figure 6, along with conductor clearance, conductor and ambient temperatures and conductor currents.

Ampacity Error

The ampacity function of the RT-TLM system is meant to provide an estimate of the additional current carrying capacity of the conductors as they approach their temperature limit. The uncertainty in that estimate is dominated by uncertainty in the temperature and interactions with the environment. Improvements in the ampacity estimator are under development.

CONCLUSION

The Promethean Devices Real-Time Transmission Line Monitor prototype has proven itself to be stable. After 150 days in the field, it is still measuring clearance temperatures, currents and estimating ampacities of a typical 500 kV transmission line in the Duke Energy system. A second generation system will soon be available that will be significantly easier to deploy and we are presently searching for suitable locations to test this system.

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