FORM: A NOVEL PRINCIPLE FOR DLR

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ABSTRACT

The use of Dynamic Line Ratings (DLR) enables transmission system operators (TSOs) to continuously adjust their maximum transmission capacity based on ambient weather conditions. The concept of FORM (FiberOptics for Rating and Measurement) provides a new solution for implementing DLR. With FORM, both the acquisition and transmission of ambient weather data takes place solely via fiber optics. A study has been conducted for the past two years in which FORM has been used to gather weather data on a 380-kV network and has been compared with measurements obtained by weather stations and forecasts based on weather models. Over the course of this study, the proof of concept and the superior functionality of FORM has been demonstrated.

INTRODUCTION

Over the past several decades, the relationship between generation and load in power systems has experienced a paradigm shift, leading to an increasing number of capacity shortfalls among transmission system operators (TSOs) worldwide. The rapid deployment of intermittent renewable sources (IRS) is a key driver behind this shift, contributing to the increase in curtailment and resdispatching—all of which incurs congestion costs that are passed on the consumer and economy as a whole. At the same time, the demand for electricity has steadily increased, owing to the growth in building electrification, e-mobility, the retirement of nuclear power plants, and global conflict. Permanent or even temporary increases in the transmission capacity of power lines can provide relief to this issue.

Though methods have existed and continue to be used to maximize transmission capacity via probabilistic or seasonal ratings, their increases are fixed and are implemented with large safety margins in place. In addition, these methods are typically based on historical data which does not accurately reflect the present situation. For example, TSOs in Canada recently dealt with temperatures exceeding 45°C in June 2021, and German TSOs now experience 40°C days. Such techniques are no longer sufficient to meet today's demands. It is necessary to consider a new approach that adequately matches the dynamic situation brought upon by new load profiles, unprecedented weather conditions, and the need to maximize (and often exceed) the rated capacity of existing lines. Dynamic Line Ratings (DLRs) offer a solution to this end by basing line ratings on ambient weather conditions in real-time.

In order to increase the capacity of transmission lines via DLR, two fundamental parameters must be considered: the maximum allowable conductor temperature and the minimum clearance distance between the line and objects beneath it. The conductor temperature, and in turn, the slack (i.e., sagging) of conductors, are influenced by operational parameters (e.g., electric current) and ambient weather conditions (e.g., wind, ambient temperature, solar irradiance). Some of the challenges in implementing DLR include the following:

- Significantly greater loads than before
- Continuously changing infrastructure/load profiles
- Aging infrastructure (40+ years old in many countries)
- More frequent and more intense weather events, on micro- and macroclimatic scales
- Deploying electronic equipment to monitor location-dependent weather conditions and physical parameters of high-voltage, multi-circuit transmission lines that span vast distances
- Finding alternatives to third-party telecommunication networks for transmitting data that meet TSO's security standards and are immune to electromagnetic noise

In light of the challenges listed above, it is clear that increasing transmission capacity is a complex undertaking that requires extensive study and evaluation of various approaches (see Fig. 1). A necessary step in performing this task is to establish regulations in the planning and operational management processes. Several countries are drafting such regulatory provisions, including the United States with the passing of Order 881 and ensuing NOPR AD22-5-000 [1], [2].

Thus, the current tasks for TSOs are to choose and evaluate an adequate approach with the following goals in mind:

- Appreciably increase transmission capacity
- Minimally reduce transmission reserve margin (TRM)
- Ensure line ratings are flexible, implementable year-round, and spatially resolved
- Ensure operational and public safety

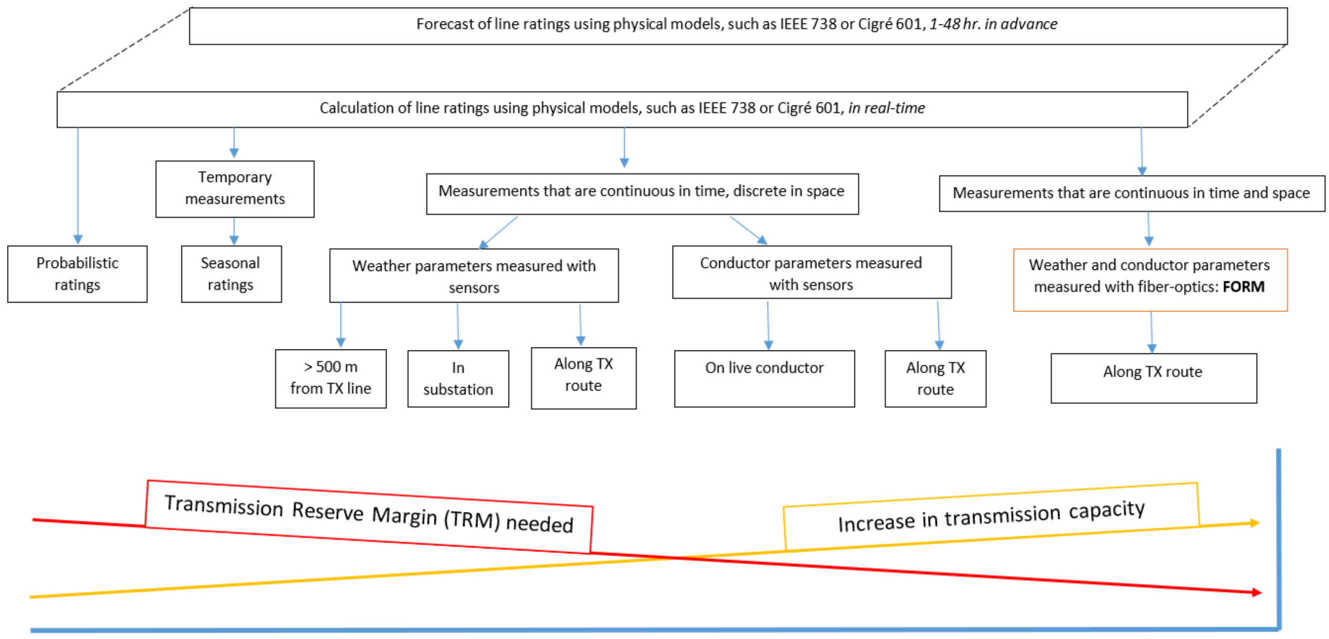

Fig. 1 Overview of methods and data acquisition options for DLR

- Ensure accessibility to DLR equipment and verifiability of measurements
- Minimize power requirements for DLR equipment

With these objectives in mind, a DLR technique based upon fiber-optic technology (FiberOptics for Rating and Measurement – FORM) was first conceived and further developed within the context of a proof-of-concept study.

METHODOLOGY

Commonly used DLR techniques (i.e., weather stations, sensors installed on conductors, Lidar, etc.) typically require an external power supply, which normally is a battery that needs to be replaced regularly. In addition to this burden, considerable effort is needed to install such devices (especially optical phase conductors – OPPCs) and often necessitates lines to be deenergized for a period of time. Because these devices typically transmit their data via public telecommunication networks, the TSO also runs the risk of exposing themselves to cyberattacks. To avoid these issues, fiber-optic technologies can be utilized and integrated with the existing fiber-optic infrastructure of transmission networks.

The application of optical fiber technology to transmission grid monitoring has been investigated extensively for a variety of purposes. Most commonly, Brillouin optical time domain reflectometry (BOTDR) and/or fiber Bragg Grating (FBG) have been used to monitor environmental loads (such as ice loading [3]–[9], wind-induced vibrations [10], and lightning strikes [3], [4]) by detecting changes in strain or temperature caused by these environmental factors. A smaller body of research has investigated fiber-optic ambient temperature measurements within the context of DLRs [6], [11]–[14]. [11] and [6] embedded fiber-optic sensors in the OPPC of a transmission line, whereas [12]–[14] used the optical ground wire (OPGW) as the sensing medium. Although an OPPC-based measurement provides the most realistic estimation of the line's temperature, most existing transmission routes do not have OPPCs already installed and would incur additional expenditure. In comparison, the vast majority of existing transmission lines use OPGWs. While an OPGW-based measurement would not include the heat generated by the conducting current, [12], [13] demonstrated that measuring the ambient temperature with the OPGW includes the heat generated by solar irradiance, preventing the need for a pyranometer or other means of irradiance measurement. Furthermore, calculating the heat generated by current flow is straightforward and well-understood.

DTS

Distributed temperature sensing (DTS) is widely used in high-voltage underground and submarine cables for monitoring purposes and can also be used with overhead transmission lines to measure the ambient temperature [15]. Within the context of this study, DTS was utilized with an OPGW to measure the combined effects of ambient temperature and solar irradiance. Stimulated Brillouin scattering was used with SiO_2 single-mode optical fibers, operating at a wavelength of 1550 nm.

Utilizing DTS with the OPGW enables the TSO to create a temperature profile of the entire transmission route with a resolution on the order of 10^{-1} m. In doing so, individual sections of the transmission route can be delineated from each other. Based on operational experience, two optical fibers are needed for this measurement [16].

Fig. 2 depicts a typical temperature profile along a 23-km line. Due to the relationship between elevation and temperature, the sagging of the lines between individual towers manifests itself as a temperature curve with roughly the same contour as the line's slack (Box a.). The towers with hood joints distort the temperature measurements at those locations due to their massive heat capacities, relative to the OPGW (Box b.). In addition to these sections with the hood joints, the sections corresponding to the substation and anchor portal do not accurately reflect the ambient temperature and are thus omitted in calculations. In determining the ambient temperature to be used in conductor temperature calculations, various lengths of the route can be considered. These sections (i.e., spans), ranging from smallest to largest, can be the distance between ordinary suspension towers, anchor pylons, towers with hood joints, or even the entire length of a route from one portal to the other.

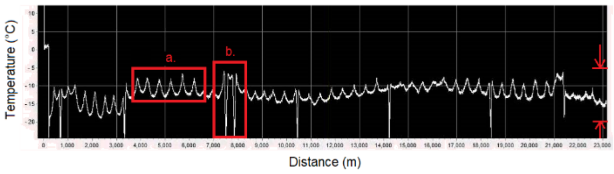

Fig. 2 Typical temperature profile along a 380-kV route, using DTS with OPGW

FOA

To determine the wind profile along a transmission line, discrete measurements of the wind speed are taken along the transmission route. Fiber-optic anemometers (FOAs) can be most conveniently placed on towers with hood joints due to their direct access to the OPGW.

The operating principle of the FOA is based on the relationship between the attenuation in an optical fiber and wind speed. In a hemispherical-cup anemometer, both the tangential velocity of the cups as well as the rotational frequency of the anemometer's axis are linearly dependent on the wind speed V_w. As the anemometer spins, the optical fiber is periodically bent in proportion to the wind speed. In order to minimize the mechanical strain on the fiber, the rotational speed of the axis is reduced and accounted for by multiplying the measured wind speed by a factor *N*. The wind speed is extrapolated from the period of the measured optical signal (i.e., the change in attenuation due to the bending of the fiber) in the following manner

$$V_w = a + 2\pi r \frac{Nb}{T} \qquad (1)$$

where *a* is the starting speed (i.e., minimum speed at which the anemometer beings to rotate, approx. 0.1 m/s), *r* the radius of the rotor, *N* the speed reduction ratio, *T* the period of the measured signal, and *b* the pressure coefficient between concave and convex hemispheres.

The periodic changes in attenuation caused by the FOA are captured and processed by an optical power meter consisting of a transmitter and receiver. In addition, the fibers containing the FOA measurements are coupled with an optical monitoring system via the fiber termination panel in the TSO's substation (see Fig. 3). This monitoring system is equipped with a special firmware that implements Eq. 1 and uses a separate interface to make the wind data available for the end-user.

Ideally, the FOAs are installed on a cantilever protruding out from the corner leg of a transmission tower (see Fig. 4). In doing so, undesirable effects caused by the structure of the tower, such as turbulence and wind shadowing, can be minimized.

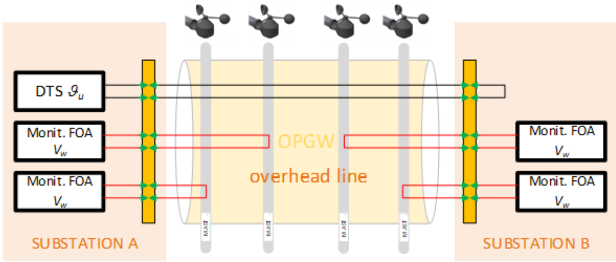

Fig. 3 Fiber layout used for DTS and FOA

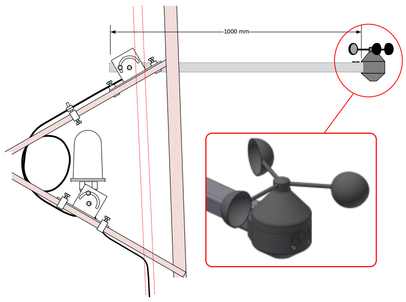

Fig. 4 Position of FOA on a cantilever

RESULTS

A new method for gathering ambient weather measurements and processing its data was developed with an emphasis on utilizing available fiber-optic infrastructure, minimally interfering with the TSO's day-to-day operations, and prioritizing secure data transmission. FORM defines the conditions for the acquisition, transmission, and analysis of measured data:

- All sensors are based on fiber-optic technology in which no external power supply is needed: DTS is used to generate a temperature profile of the transmission line, and FOAs are used for a local measurement of the wind speed along the line
- The OPGW is used for data transmission and thus there is no need for using public telecommunication networks
- All of the measurement equipment is compatible with existing transmission lines and does not require the line to be shut off during installation
- The monitoring equipment is installed at the endpoints of

the transmission route (e.g., substations, switching stations)

FORM was implemented in a proof-of-concept study on three different 380-kV transmission networks. Initial results showed that the thermal rating of the lines considered was well beyond their static limits. An application that processes the field data and displays the relevant information on a dashboard in real-time was developed in order to give the operator as much insight as possible (see Fig. 5). Future work includes integrating this application with the TSO's SCADA system.

Fig. 5 Dashboard developed for FORM

Comparison of measurements

Temperature measurements taken from a commercially available weather station were compared with those taken by the OPGW over a long period of time for one of the transmission routes. Fig. 6 shows a comparison of the two measurements over one week (zoomed in for legibility) and it is clear that there is a high degree of correlation between the two signals. At night, the measurements are very similar (cross-correlation factor of 0.98), but during the day, the impact of solar irradiance on the OPGW reading is apparent. The influence of solar irradiance on the temperature measurement is accounted for in the model used in this study.

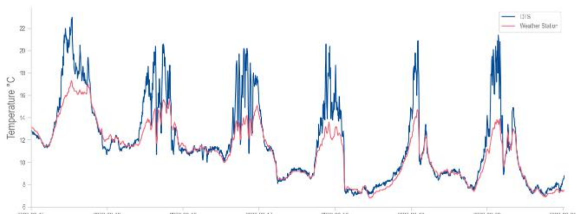

Fig. 6 Comparison between OPGW (blue) and weather station temperature (red) over 1-week period

Similarly, the FOA wind measurements were very similar with those taken by the weather station. Both devices were installed one meter apart from each other on the same corner of a transmission tower and were positioned to be at the same elevation as the lowest line in the conductor bundle. It was assumed that these devices would then be subjected to the same atmospheric conditions as the conductors.

An exemplary plot of wind measurements over a two-month period is shown in Fig. 7 and exhibits a cross-correlation of 0.87, implying a high degree of similarity between the FOA and weather station's wind readings. Some of the differences could be attributed to the physical operation of each device (ultrasonic vs. mechanical cup anemometer) and the different sampling rates of each device.

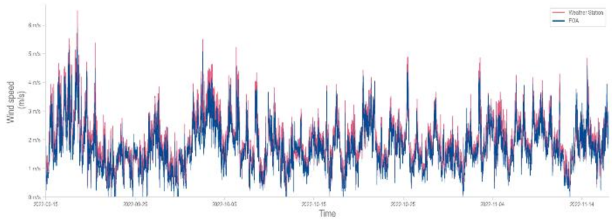

Fig. 7 Comparison between FOA (blue) and weather station wind speeds (red) over 2-month period

Finally, temperature and wind measurements taken by the OPGW and FOAs were compared with commercial weather forecasts provided for the transmission route under consideration. The comparative analysis showed significant differences between the measured and forecasted data, especially for the wind data (see Fig. 8). One can conclude that the specific meteorological conditions along transmission lines cannot be accurately represented by weather models/forecasts.

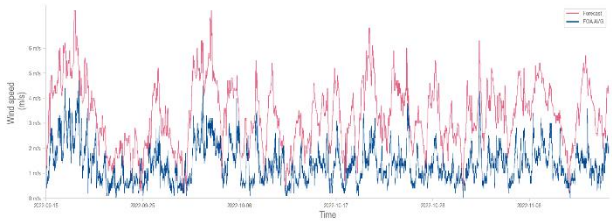

Fig. 8 Comparison between FOA (blue) and forecasted wind speeds (red) over 2-month period

CONCLUSION

FORM provides a straightforward and practical framework for implementing reliable measurements in real-time for DLRs. This study provides evidence of the first DLR solution in which

- conditions along the entire transmission line are known
- all data is transmitted securely via the TSO's own network
- line ratings are based upon evaluating every span, rather than just a select number of discrete spans.

Temperature and wind measurements acquired by FORM were compared with those gathered by commercially available weather stations, and the two signals exhibited a high degree of correlation. Furthermore, measurements obtained with FORM proved to be more accurate than forecasted values, underscoring the importance of using measured data in a DLR implementation. Looking ahead to the future, data from FORM could also one day be used to help refine weather models, be it for DLR or general weather forecasting purposes.

Acknowledgments

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