Application of fiber-optics to FERC Order 881 on ambient-adjusted ratings (AAR) and dynamic line ratings (DLR)

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***Abstract*—Transmission capacity shortfalls are a major bottleneck towards many efforts in electrification and renewable energy deployment. One relatively rapid and cost-effective solution to increase transmission capacity is to operate transmission lines as close to their thermal limits as possible, either via ambient-adjusted ratings (AAR) or dynamic line ratings (DLR). However, current AAR and DLR technologies must overcome several challenges to be adopted widespread. Motivated by the desire to reduce the financial and operational hurdles towards implementing AAR and DLR, a novel technique for thermally rating transmission lines using fiber-optic sensors was developed. This technique, known as FORM (FiberOptics for Rating and Measurement), meets the calculation requirements of the US rulemaking on AAR in FERC Order 881 and can also be used for DLR. FORM uses distributed temperature sensing (DTS) with the optical ground wire (OPGW) of the transmission network to spatially and temporally resolve a temperature measurement that reflects both the ambient temperature and solar heating. This measurement alone suffices for a reasonably accurate AAR or DLR implementation but specially designed fiber-optic anemometers (FOAs) can be installed on transmission towers and connected to the OPGW to improve the accuracy of FORM. The conductor temperature was calculated using FORM and was then compared with the same calculation using standard DLR models (CIGRÉ TB 601/IEEE Std. 738) on a 380-kV line over a 12-month period.**

***Index Terms*—dynamic line ratings (DLR), ambient adjusted ratings (AAR), thermal line ratings, FERC Order 881, distributed temperature sensing (DTS), fiber optics**

I. INTRODUCTION

The urgency to decarbonize the electricity sector has been met with an almost equally rapid proliferation of renewable energy resources and electrification across many industries. While encouraging, these efforts are stymied by the lack of available transmission capacity, contributing to the ever-growing interconnection queue for new renewable generation, now averaging five years in the US, up from two years in 2008 [1]. Transmission capacity shortfalls also have financial consequences when the most inexpensive generation – which often comes from solar PV or wind units – cannot be delivered, forcing more expensive generation to be dispatched, leading to so-called congestion costs that are passed on to the consumers. In the US, these congestion costs have tripled relative to 2016 levels at an estimated 20.8 billion USD in 2022 with similar patterns having been observed in other countries [2].

There are several methods for increasing transmission capacity, such as building new infrastructure and upgrading conductors, but are often costly and time-consuming, requiring coordination among transmission owners (TOs), transmission system operators (TSOs), landowners, and regulatory agencies. A faster and more cost-effective solution is to adjust maximum line ratings based on measurements or estimates of the line temperature, which includes ambient-adjusted rating (AAR) and dynamic line rating (DLR) techniques. The maximum power that a transmission line can deliver (i.e., line rating) can be limited electrically by voltage or phase stability issues but is more often constrained by thermal limits, especially for shorter lines (<250 km) [3]. Historically, thermal line ratings have been set to static values or have been determined seasonally based on conservative estimates of the ambient weather conditions, but both of these methods rarely reflect the line's true rating since the actual ambient weather conditions typically deviate from the static assumptions. The static rating may even exceed the true thermal limit of the conductor on hot, sunny days with little wind and high electricity demand.

With the advent of reliable medium-range weather forecasts and Supervisory Control and Data Acquisition (SCADA) systems, transmission providers (TPs) and TSOs began adjusting their thermal line ratings based on hourly air temperature forecasts, known today as AAR [4]–[7]. While simplistic in principle, AAR has proven to be an effective way for increasing transmission capacity, albeit modestly, with a review in [8] reporting an average rating increase of 5-10%, relative to the static rating. To unlock more potential, researchers also began investigating DLR, which incorporates direct measurements of the line parameters (e.g., line temperature, sag, tension), estimates of line temperature based on ambient weather measurements (e.g., air temperature, wind, solar irradiance), or a combination of both. Capacity increases from DLR range from case to case but one study from the Belgian TSO Elia reported increases of 32-56% using vibration-based DLR sensors [9].

Although many TPs within the US began implementing AAR and/or DLR on their own, the US Federal Energy Regulatory Commission (FERC) passed Order 881 in 2021, requiring all TPs to implement AAR on lines that they service [10]. While FERC acknowledges that DLRs would provide greater transmission capacity increases compared to AARs, FERC decided to limit the scope of Order 881 to only include AAR for now but are continuing to investigate a future rulemaking on DLR with the Notice of Proposed Rulemaking (NOPR) in docket AD22-5-000 [11]. Part of this reasoning may stem from the fact that implementing DLR with current techniques is costly: estimates from various TOs in the US range from 100,000 to 1 million USD per line [10]. Conventional DLR techniques typically utilize weather stations, conductor-mounted sensors, or LiDAR, which incur costs not only from the devices themselves but also from their installation, service, and maintenance [12].

Motivated by the desire to reduce the financial and operational hurdles towards implementing AAR and DLR, a novel line rating technique was developed that utilizes the existing fiber-optic infrastructure of transmission networks. Known as FORM (FiberOptics for Rating and Measurement), this technique uses the network's optical ground wire (OPGW) to both measure ambient weather parameters and to securely transmit that data back to the operator. FORM has been studied and implemented in a proof of concept within the 50Hertz Transmission GmbH territory in Germany for the past three years.

II. BACKGROUND

The most widely used methods for calculating line ratings are documented in CIGRÉ TB 601 [13] and IEEE Std. 738 [14]. These methods are based upon the assumption that the conductor temperature T_c (and by extension, additional current capacity) can be reasonably estimated by knowing the ambient temperature T_a, wind speed v, wind direction θ, sun exposure, and line current I_c in real-time. Collectively, these parameters are used to iteratively calculate solar irradiance P_s, Joule heating $P_j(I_c, T_c)$, convection $P_c(v, \theta, T_c, T_a)$, and radiation $P_r(T_c, T_a)$, which are then used in Eq. 1,

$$T_c\left(t+\Delta t\right) = T_c(t) + \frac{P_{s,c} + P_j - P_{c,c} - P_{r,c}}{c_c}\Delta t, \quad (1)$$

where c_c is the heat capacity of the conductor and the subscript c denotes the conductor. It is widely accepted that other factors (e.g., air pressure, humidity, precipitation) can influence T_c but are normally negligible. A study in [15] determined that, on average, including these second-order effects improved the accuracy of the calculation by only 0.59°C.

Despite needing only a relatively small number of meteorological parameters to estimate the conductor temperature, obtaining these measurements with an appropriate spatial resolution is challenging. Transmission lines often span vast distances (especially in the US, China, and Brazil) and can straddle multiple microclimates (e.g., due to mountains, waterways). A common compromise among DLR techniques is to identify the "critical spans" that tend to be the warmest and to then install sensors at those locations, be they weather instruments, optical sensors, or other devices. Although this approach is an improvement over utilizing measurements from third-party weather services, these critical spans may change over time, especially as the global climate changes.

One possibility for obtaining spatially-resolved weather measurements along a transmission line is to utilize distributed temperature sensing (DTS) with the line's OPGW. DTS is a widely used technology in cable temperature monitoring for offshore wind farms and underground applications, and is compatible with OPGWs [16]. Because the speed of light in a vacuum is known and the index of refraction is temperature-dependent, sending pulses of light through an optical fiber (i.e., "pumping") and measuring the backscattering time allows the temperature to be spatially and temporally resolved. In this study, stimulated Brillouin scattering was used in two of the OPGW's SiO_2 single-mode fibers at a wavelength of 1550 nm to resolve the temperature on the order of 10 cm every five minutes. The DTS instrument was installed in the substation belonging to the TO and did not require the line to be deenergized during its installation. Because the DTS instrument provides up to four channels, up to four OPGWs can be simultaneously monitored—allowing one device to theoretically provide line ratings on four lines.

Because the OPGW is not shielded in any way, the temperature recorded by the DTS system does not reflect the true air temperature. In fact, it is heated by solar irradiance, cooled by convection, and radiates heat:

$$T_{OPGW}\left(t+\Delta t\right)=T_{OPGW}(t)+ \frac{P_{s,OPGW}-P_{c,OPGW}-P_{r,OPGW}}{c_{OPGW}}\Delta t. \tag{2}$$

A. Assumptions in FORM

Convective cooling primarily depends on the temperature difference between the air and the body that is being cooled. This relationship to the temperature difference is highly non-linear, regardless of whether wind-induced (forced) convection is dominant (generally for $v > 0.5$ m/s) or natural convection is dominant ($v < 0.5$ m/s, based on temperature-dependent circulation of air) [13]. As such, $P_{c,OPGW}$ will be small in general and much smaller than $P_{c,c}$ since the temperature gradient between the current-carrying conductor and air is much larger than the gradient between the OPGW and air. However, $P_{c,c}$ can be conservatively estimated using T_{OPGW} as T_a if it is assumed that natural convection is always the dominant form of convection. This assumption will always yield a smaller $P_{c,c}$ than the true value, since $(T_c - T_a) > (T_{OPGW} - T_a)$ and v is often greater than 0.5 m/s.

If the TO/TP wishes to take wind measurements into account to calculate forced convection, FORM offers the flexibility to integrate specially-designed fiber-optic anemometers (FOA) with the OPGW, see Fig. 1. A fiber is embedded in the FOA that is gently bent as the shaft spins in response to the wind. By measuring the periodic change in the fiber's attenuation, the wind speed can be resolved. Because this measurement is obtained passively using pulses of light sent through the OPGW, no external power supply is needed. In addition, the data recorded by the FOA is securely transmitted to the TP/TO via the OPGW. More details are provided in [12].

Radiation also depends on the temperature difference between the OPGW/conductor and air but is proportional to the fourth power of that difference. Consequently, the heat that the OPGW radiates is minuscule compared to the conductor's radiation since $(T_c - T_a)^4 >> (T_{OPGW} - T_a)^4$. Thus, $P_{r,c}$ should be calculated under the conservative assumption that $(T_c - T_{OPGW})^4 \approx (T_c - T_a)^4$.

To err on the side of caution, [13], [14] suggest assuming that the sun is always shining when calculating P_s and to make conservative assumptions of the line's absorptivity and ground's reflectance (albedo). However, it has been shown in [12] that T_{OPGW} will rise above T_a when the sun is shining, and this relative difference between the temperature of a sun-exposed body and T_a is how thermopile pyranometers measure P_s. Furthermore, since P_s depends linearly on D, it can be readily assumed that

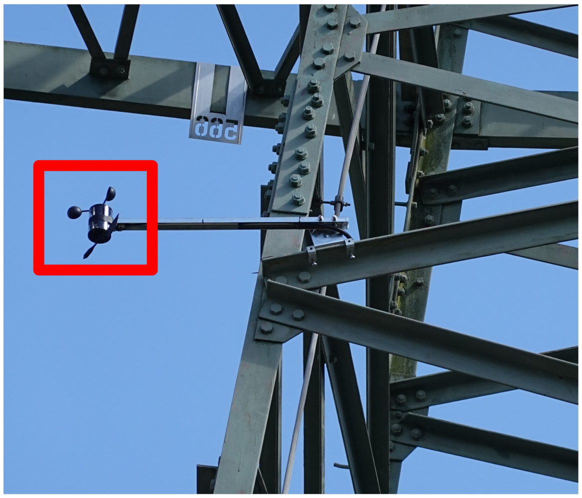
Fig. 1. Fiber-optic anemometer (FOA) on transmission tower

$$P_{s,c} \approx \frac{D_c}{D_{OPGW}} P_{s,OPGW}. \tag{3}$$

Since $P_{r,OPGW}$ and $P_{c,OPGW}$ are assumed to be small, $P_{s,c}$ can be directly calculated in terms of T_{OPGW}.

$$P_{s,c} \approx \frac{D_c c_{OPGW}}{D_{OPGW}\Delta t}\left(T_{OPGW}(t+\Delta t) - T_{OPGW}(t)\right) \tag{4}$$

Thus, measuring T_{OPGW} provides a direct way to estimate $P_{s,c}$ that reflects the true solar irradiance (factoring in cloud cover, absorption, albedo, etc.) and is a significant improvement over the assumptions used in the standard models.

Combining Eq. 4 with Eq. 1, T_c can be estimated in the following manner

$$T_c\left(t+\Delta t\right) \approx T_c(t) + \Delta t \frac{P_j - P_{c,c} - P_{r,c}}{c_c} + \frac{D_c}{D_{OPGW}} \frac{c_{OPGW}}{c_c}\left(T_{OPGW}(t+\Delta t) - T_{OPGW}(t)\right) \tag{5}$$

where $P_{c,c}$ and $P_{r,c}$ are calculated using T_{OPGW} under the previously described assumptions.

B. Evaluation of FORM

T_c was calculated over a period of 12 months for a 650 m section of a 380-kV transmission line rated for 40°C using three methods:

1) FORM (Eq. 5) using T_{OPGW} and no wind measurements: $T_{c,\,FORM,\,no\,FOA}$
2) FORM (Eq. 5) using T_{OPGW} with wind measurements: $T_{c,\,FORM,\,w/\,FOA}$
3) CIGRÉ TB 601 (Eq. 1) using T_a with wind measurements: $T_{c,\,Cigre}$

To yield the most accurate comparison, T_{OPGW} was averaged over the 650 m section, T_a was measured directly on-site site using a commercially available weather station, v was measured directly on-site using an FOA, and θ was obtained from a third-party weather service.

Fig. 2 shows the temperature variation of T_c using the three methods described above as well as T_a and T_{OPGW} on a warm but overcast summer day with a high temperature of 33°C. Due to the warm weather and loading, the conductor was operating near its thermal limit (40°C). Cloud cover is reflected in the fact that T_{OPGW} is almost equal to T_a. The shortcomings of assuming that the sun is always shining are clearly shown in the more than 10°C deviation of $T_{c,Cigre}$ from the other two T_c calculations using FORM. $T_{c,Cigre}$ rapidly increases as soon as the CIGRÉ model assumes that the sun rose (around 5:30 AM) and remains well above the other two T_c calculations for the entire day. The finely resolved peaks and valleys in T_{OPGW} compared to the relatively flat profile of T_a between 12:00 and 18:00 reflect not only the fluctuations in solar heating but are also a result of the DTS system's finer sampling time.

It is also important to point out the temperature deviation between $T_{c,FORM,no\,FOA}$ and $T_{c,FORM,w/\,FOA}$ from 00:00 to 06:00. During that period, a sustained moderate breeze was cooling the conductor via forced convection which could not be registered without directly measuring v, leading to a 2-4 degree difference between the two curves. It is clear from Fig. 3a that as the wind speed increases, the average temperature deviation between $T_{c,FORM,no\,FOA}$ and $T_{c,FORM,w/\,FOA}$ increases. While this may seem problematic, for the site under consideration, v was below 1 m/s for over 60% of the time and exceeded 4 m/s less than 5% of the time (see Fig. 3b). Nevertheless, for lines that are located in windy areas, it may be worth the additional expenditure to install FOAs.

Ultimately, using FORM without measuring v yielded reasonably accurate calculations of T_c for the site under consideration. Fig. 4 shows the probability of $T_{c,FORM,no\,FOA}$ deviating from $T_{c,FORM,w/\,FOA}$ at different temperature ranges. For over 70% of the year, this average deviation was less than 5°C, corresponding to a capacity difference of less than 50A for typical conductors (e.g., ACSR) [3]. In addition, the difference between $T_{c,FORM,no\,FOA}$ and $T_{c,FORM,w/\,FOA}$ was always positive, implying that using FORM without FOAs adheres to a more conservative, "worst-case scenario" operation.

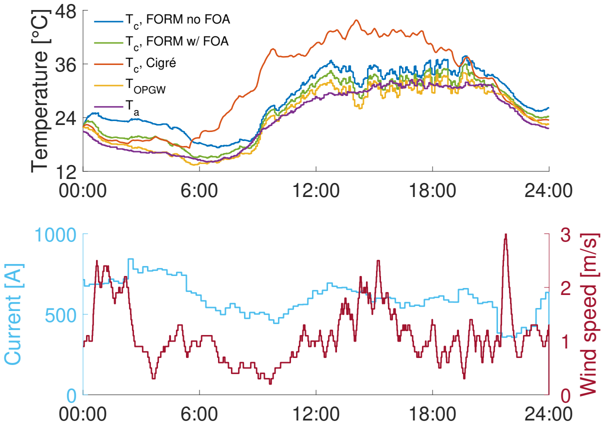

Fig. 2. Manifestation of erroneous solar irradiance assumption from CIGRÉ 601/IEEE 738 models on July 14, 2023 during daytime periods of cloud cover

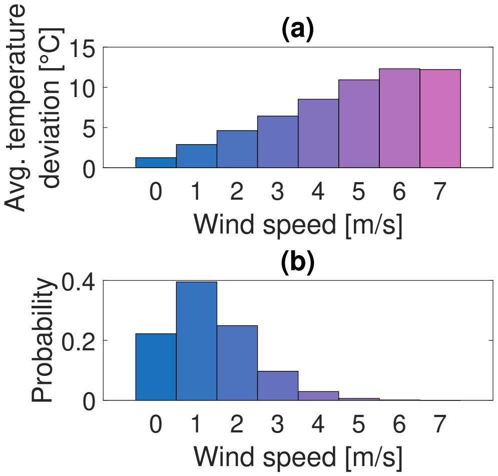

Fig. 3. Average temperature deviation between conductor temperature calculations $T_{c,FORM,no\,FOA}$ and $T_{c,FORM,w/\,FOA}$ vs. wind speed (a) and probability of a given wind speed occurring during the one year period (b)

III. DISCUSSION

FORM provides a simple and effective way to implement AAR, as per its definition in Order 881. In Section I of Order 881, it is specified that ambient-adjusted line ratings must

1) apply to a time period of not greater than one hour,
2) reflect an up-to-date forecast of ambient air temperature across the time period to which the rating applies,
3) reflect the absence of solar heating during nighttime periods, and
4) be calculated at least ever hour.

Commercially available DTS systems allow T_{OPGW} – and, in turn, line ratings – to be calculated every several minutes at every location along a transmission line. Furthermore, measuring T_{OPGW} reflects a true measurement of both T_a and solar heating, during daytime and

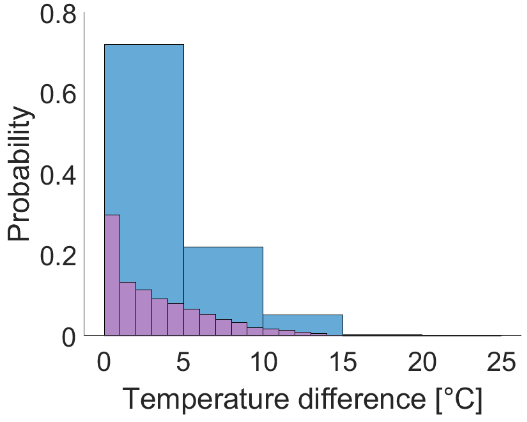

Fig. 4. Probability of a given temperature deviation between $T_{c,\,FORM,\,no\,FOA}$ and $T_{c,\,FORM,\,w/\,FOA}$

nighttime periods.

For TPs/TOs looking to comply with future rulemakings on DLR, which is defined in [10], [11] to

1) apply to time period of no greater than one hour, and
2) reflect up-to-date forecasts of inputs such as (but not limited to) ambient air temperature, wind, solar heating intensity, transmission line tension, or transmission line sag,

FORM is an attractive option. Simply measuring T_{OPGW} alone complies with the calculation requirements since it accurately reflects solar heating intensity every several minutes, but FORM can also include onsite wind measurements using FOAs.

IV. Conclusion

A novel thermal line rating technique that is compliant with the calculation requirements of current rulemakings on AAR as well as with potential future rulemakings on DLR is presented. Unlike other discrete sensor based techniques, FORM makes use of DTS technology to obtain a spatially-resolved line rating using the existing fiber-optic infrastructure of the transmission line. The DTS device is installed in the substation belonging to the TP/TO and does not require the line to be deenergized during installation. FORM is also modular in that the possibility exists to install fiber-optic anemometers to refine the calculation of the conductor temperature as the user sees fit. These FOAs securely transmit their data to the central server via the OPGW in contrast to many DLR sensors that use public telecommunication networks. Should an FOA become inoperable, the thermal line rating process can still continue using a reasonably accurate variant of FORM that requires no wind measurements. Based on a year's worth of operational data, this particular variant requiring no wind measurements has been found to be within 5°C of the conductor temperature calculation with wind measurements for over 70% of the time.

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