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APPLIED RESEARCH

Facility Rating Standards Review and Proposed Methodology for FERC Order 881 AAR Calculation

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ABSTRACT FERC rule 881 requires the use of ambient-adjusted ratings (AAR) instead of standard static line ratings (SLR) to ensure more precise assessments of the maximum transfer capability of transmission lines. AAR offers several advantages, resulting in improved transfer capacities. However, the practical details of calculations of AARs require careful and detailed consideration. This paper describes the rationale, procedures and technical references used as a basis for determining AARs for FERC Order 881 compliance. IEEE standards concerning the individual power facilities are reviewed for references to ambient temperature and solar heating. The formulas, references and other relevant information are consolidated in the paper providing the necessary information to perform AAR calculations. Additionally the paper provides recommendations on developing, where applicable, conservative equipment-type rating scaling factors to be used across a utility's fleet.

INDEX TERMS FERC 881, AAR, transformer rating, facility ratings, circuit breaker rating, resiliency, reliability.

I. INTRODUCTION

Transmission line ratings have evolved significantly with the growing need for more efficient and reliable grid operations. In the past, static methodologies were used to determine these ratings, often resulting in conservative estimates that underutilized the existing infrastructure. Static line ratings, typically based on peak summer conditions, do not account for changing ambient conditions, leading to inefficiencies in grid management.

The shift from static to Dynamic Line Ratings (DLR) represents a significant advancement in how utilities manage the grid. DLR adjusts ratings in real-time based on current environmental conditions, offering capacity increases of 10% to 30% over static ratings [21], particularly during cooler periods. For example, a U.S. Department of Energy report indicates that DLR can boost real-time transmission capacity by at least 30%. Additionally, reports from the International Renewable Energy Agency and the Belgian grid operator Elia show that DLR can lead to a 5% to 20% increase in ratings, improving market dispatch efficiency and supporting the integration of renewable energy [18]. In the UK [20], the implementation of DLR has underscored the critical role of precise weather forecasting and advanced grid monitoring systems in optimizing transmission efficiency. The UK's experience shows that by leveraging accurate weather data, especially wind predictions, transmission capacities can be enhanced, which, in turn, leads to more effective use of existing infrastructure.

Ambient-Adjusted Ratings (AAR) present a viable alternative to both static and fully dynamic ratings, offering a balance between efficiency and practicality.

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AAR methodologies adjust line ratings based on measured temperature variations, providing a more accurate reflection of the transmission line's capacity.

In the US, requirements for the implementation of AARs set forth in FERC Order 881 [14] call for utilities to analyze methodologies found in industry standards to derive new ratings for transmission lines and other electrical station/substation components. While transmission line rating development, based on a variety of ambient factors, is routinely performed throughout the industry, utilities typically specify required ratings from the manufacturers for other equipment (e.g. transformers, circuit breakers, disconnect switches, etc.) and utilize the same rating across all ambient temperatures. FERC Order 881's requirements surrounding the calculation of AARs, requires adjustment to normal (continuous) and emergency ratings on the basis of ambient temperature changes and the impact of solar heating to establish separate day/night ratings. Other requirements of FERC Order 881, such as the defining temperature "zones", weather forecasts, seasonal ratings, etc., are not discussed in this paper. Each individual system operator is developing their individual response strategies for compliance with the FERC order. Several guideline and opinion documents have been published by NYISO [17], MISO [19], and CAISO [15]. A very detailed review paper, including simulations of FERC 881 order results on a large power network, was also published by Cheung [16]. However, while these documents describe individual considerations and approaches, it is important to provide an even more detailed analysis – which is provided in this paper.

The following paper compiles various industry standards for substation equipment and analyzes their requirements for adjusting normal and emergency ratings based on ambient temperature changes and solar heating. Finally, the report provides, where possible, a conservative approach for scaling different equipment-type ratings that can be applied across all equipment within a utility's fleet. The following methodology serves as an alternative to the individual analysis of different equipment for variations in manufacturer/installation date/model, etc. by making conservative assumptions on the different parameters used in the calculation of the ratings. These results may serve as a means to more expeditiously comply with the requirements of FERC order 881, or serve as an approximation when equipment data is not available for a full computation. The formulas and assumptions presented in the paper, however, may also be used to calculate AARs on an individual basis when the required data is available. The results presented in the following paper represent the application of the methodology on a sampling of equipment found in the Tri-State Generation and Transmission footprint.

II. TRANSFORMER RATINGS

A. GENERAL ASSUMPTIONS

FERC Order 881 Part 47 [14] requires ratings that are valid for periods no longer than 1 hour, and are thus adjusted based on the current ambient temperature. Oil-filled transformer temperature ratings are based on a 24-hour average due to the thermal mass of the transformer construction and the insulating oil. As such, the ambient temperatures that are referred to in the documentation below are 24-hour average temperatures and ought to be updated on a rolling 24-hour basis to accurately represent the current impact of ambient temperature on the internal transformer temperature.

Unlike other facilities where the critical temperature used in establishing ratings is based on material properties of the conducting or interrupting elements of the device (i.e. thermal expansion of a transmission conductor prior to exceedance of sagging limitation), transformer temperature limits are often established to guarantee a certain longevity of the device, and exceedance of the design temperature may not cause physical damage to the facility, instead it may shorten the life of the facility. Therefore, in the calculation of the below ratings, the adjustments to the ambient temperatures are implemented such that the design temperatures, are not exceeded, therefore not incurring accelerated loss of life of the device.

B. CONTINUOUS RATINGS

IEEE C57.91-2011 [5] "IEEE Guide for Oil Immersed Power Transformers" Section VII, "Calculation of temperatures", identifies the correlation between transformer load ratios as a function of the ambient temperature and the various transformer characteristics. These formulas were applied to test data from various transformers across the Tri-State footprint to develop a basis for increasing and decreasing the normal rating with different ambient temperatures. The standard identifies three critical components in the determination of the winding hottest-spot temperature:

$$\Theta_H = \Theta_A + \Delta\Theta_{TO} + \Delta\Theta_H \tag{1}$$

where

- Θ_H is the winding hottest-spot temperature, $^\circ C$
- Θ_A is the average ambient temperature during the load cycle to be studied, $^\circ C$
- $\Delta\Theta_{TO}$ is the top-oil rise over ambient temperature, $^\circ C$
- $\Delta\Theta_H$ is the winding hottest-spot rise over top-oil temperature, $^\circ C$

Ambient temperature for transformers is typically assumed to be 30 °C, however for the purposes of calculating the transformer ambient adjustments, the 24 hour- average ambient temperatures will be varied from −10 °C to 40 °C.

For continuous rating analysis, the ultimate top oil and hottest spot top oil temperatures are replaced into the formula:

$$\Delta\Theta_{TO,U} = \Delta\Theta_{TO,R}\left(\frac{K_U^2 R + 1}{R + 1}\right)^n \tag{2}$$

where

- $\Delta\Theta_{TO,R}$ is the top-oil rise over ambient temperature at rated load on the tap position to be studied, $^\circ C$
- $\Delta\Theta_{TO,U}$ is the ultimate top-oil rise over ambient temperature for load L, $^\circ C$

- K_U is the ratio of ultimate load L to rated load, per unit
- n is an empirically derived exponent used to calculate the variation of $\Delta\Theta_{TO}$ with changes in load. The value of n has been selected for each mode of cooling to approximately account for effects of change in resistance with change in load. See Table 4 in [5].
- R is the ratio of load loss at rated load to no-load loss on the tap position to be studied

$$\Delta\Theta_{H,U} = \Delta\Theta_{H,R} K_U^{2m} \tag{3}$$

where

- K_U is the ratio of ultimate load L to rated load, per unit
- m is an empirically derived exponent used to calculate the variation of $\Delta\Theta_H$ with changes in load. The value of m has been selected for each mode of cooling to approximately account for effects of changes in resistance and oil viscosity with changes in load. See Table 4 in [5].
- $\Delta\Theta_{H,U}$ is the ultimate winding hottest-spot rise over top-oil temperature for load L, $^\circ C$
- $\Delta\Theta_{H,R}$ is the winding hottest-spot rise over top-oil temperature at rated load on the tap position to be studied, $^\circ C$

IEEE C57.91 Section 7.2.6 Table 4 in [5], provides exponents m and n for temperature rise equations based on the cooling type of the transformer. Most transformers employ, either single or multiple cooling stages of types ONAN, ONAF or OFAF, as such, the below analysis uses $m = 0.8$ and $n = 0.8/0.9$.

The remaining variables are found in manufacturer transformer test report which indicate, either based on actual measurement or calculated values, the load losses and no load losses (to calculate R), the top-oil rise over ambient temperature $\Delta\Theta_{TO,R}$ and the winding hottest-spot rise of top-oil temperature.

Application of the above formulas to a sample of Tri-State transformer test reports, selected to represent the range of transformer ages and types owned by Tri-State, resulted in the following data and subsequent recommendations shown in in Fig. 1 and in Fig. 2 and in Table 1.

For comparison, IEEE C57.91-2011 Section 6.4 Table-3 provides a table used for quick approximation. The standard states conservative approximations are used in its tables. However, the analysis performed using transformer test data suggests that more conservative values are recommended.

C. EMERGENCY RATINGS

Tri-State standards for transformer emergency ratings consist of a Long Term Emergency (LTE) rating of 110% for 4 hours, and a Short Term Emergency (STE) rating of 125% for 30 minutes. The goal of calculating emergency ratings adjustments for varying ambient temperatures is also to maintain the same final temperature rise as the rated

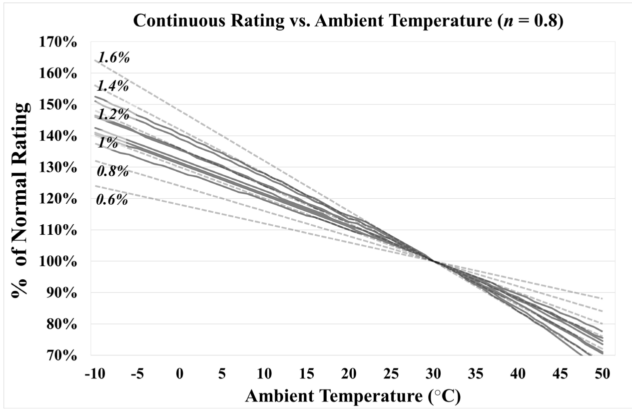

FIGURE 1. Continuous rating vs. Ambient temperature of eight sampled Tri-state transformers in ONAN mode.

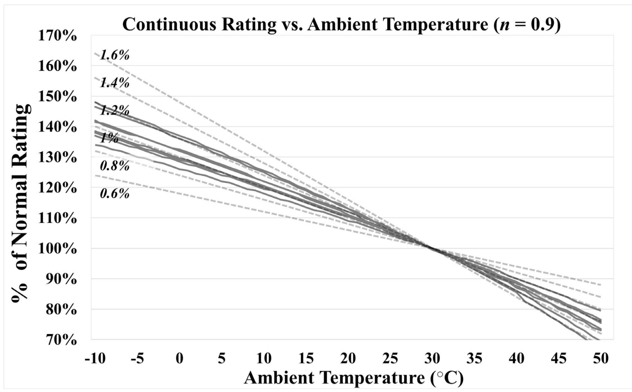

FIGURE 2. Continuous rating vs. Ambient temperature of eight sampled Tri-state transformers in ONAF/OFAF mode.

temperature. During normal operation, a transformer will be loaded to a certain percentage of its normal rating prior to the emergency conditions. The recommendations assume that the transformer is at 80% of its rated continuous temperature prior to emergency loading conditions.

TABLE 1. Continuous rating adjustments due to ambient temperatures as % of MVA rating[1].

Type of cooling	Decrease rating for each °C higher temperature	Increase rating for each °C lower temperature
ONAN	1.6	0.9
ONAF/OFAF	1.4	0.75[2]

[1]Other values may be used based on individual performance or manufacturer recommendation [2]Sample data recommends limiting to (0.9), however deference is given to the IEEE C57.91-2011 Table 3

Derivation of the emergency ratings introduces additional variables for the calculation of the top oil temperature rise over ambient and the hottest spot rise over top-oil as defined in IEEE C57.91-2011 Section VII. Calculation of temperatures. However, Appendix C, page 51 states that "The winding hot-spot rise over top oil, $\Delta\Theta_{TO}$ is considered to be instantaneous. Only where current discontinuities occur will some consideration be given to the winding time-constant.'' Therefore, the time component in equation 4 is not considered. The above assumptions are applied to the same sample dataset utilized in the calculation of the continuous rating adjustments using $t = 0.5$ and $t = 4$ as the time component, and the correct rating factor identified for each ambient temperature.

$$\Delta\Theta_{TO} = (\Delta\Theta_{TO,U} - \Delta\Theta_{TO,i})\left(1 - e^{-\frac{t}{\tau_{TO}}}\right) + \Delta\Theta_{TO,i} \tag{4}$$

where

- $\Delta\Theta_{TO}$ is the top-oil rise over ambient temperature, $^\circ C$
- $\Delta\Theta_{TO,U}$ is the ultimate top-oil rise over ambient temperature for load L, $^\circ C$
- $\Delta\Theta_{TO,i}$ is the initial top-oil rise over ambient temperature for $t = 0$, $^\circ C$
- e is the base of natural logarithm
- τ_{TO} is the oil time constant of transformer for any load L and for any specific temperature differential between the ultimate top-oil rise and the initial top-oil rise, h

$$\Delta\Theta_H = (\Delta\Theta_{H,U} - \Delta\Theta_{H,i})\left(1 - e^{-\frac{t}{\tau_w}}\right) + \Delta\Theta_{H,i} \tag{5}$$

where

- t is the duration of load, h
- $\Delta\Theta_H$ is the winding hottest-spot rise over top-oil temperature, $^\circ C$
- $\Delta\Theta_{H,U}$ is the ultimate winding hottest-spot rise over top-oil temperature for load L, $^\circ C$
- $\Delta\Theta_{H,i}$ is the initial winding hottest-spot rise over top-oil temperature for $t = 0$, $^\circ C$
- τ_w is the winding time constant at hot spot location, h

The resulting long and short term ratings indicate that change in overload capability associated with the 30 minute and 4 hour ratings changes gradually as temperatures increase and decrease. Therefore an adjustment factor is also applied to the emergency ratings as a percentage of the ambient-adjusted continuous rating.

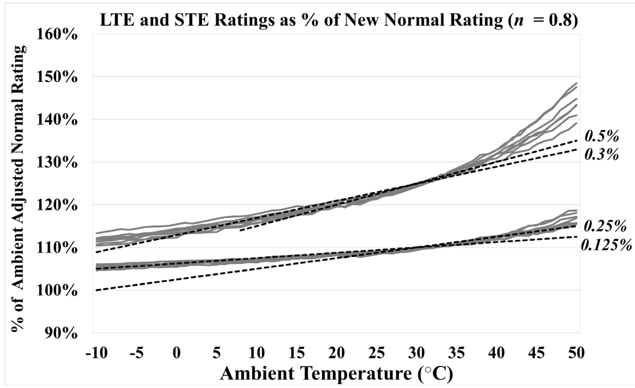

FIGURE 3. Emergency ratings with trend lines for ONAN transformers.

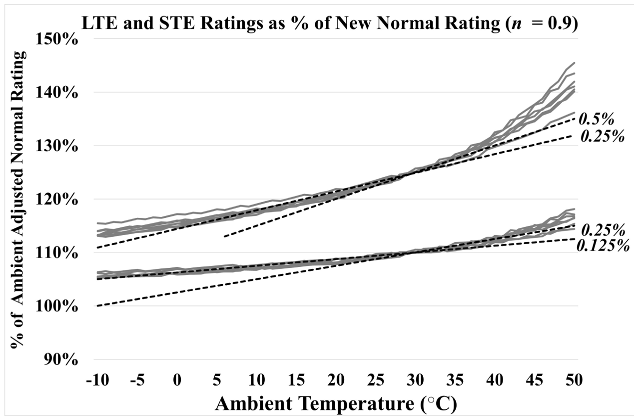

FIGURE 4. Emergency ratings with trend lines for ONAF/ONAF transformers.

TABLE 2. Emergency rating adjustments due to ambient temperatures as % of MVA rating[1].

Type of cooling	Decrease rating for each °C higher temperature		Increase rating for each °C lower temperature	
	STE	LTE	STE	LTE
ONAN	0.5	0.25	0.3	0.125
ONAF/OFAF	0.5	0.25	0.25	0.125

[1]Other values may be used based on individual performance or manufacturer recommendation. Updated emergency ratings are a percentage of the Ambient Adjusted Normal Rating

III. SUBSTATION RIGID BUS-CONDUCTOR RATINGS

A. GENERAL ASSUMPTIONS

Like transmission conductors, the ratings of substation bus depend on several ambient factors related to the geographic location of the bus. For the purposes of the analysis performed in this study, all other ambient variables (elevation, wind-speed, etc.) are fixed to align with the current assumptions and the ambient temperature adjusted by 1°C increments. Ampacities of rigid bus are calculated based on the process outlined in IEEE Std 605-1998 [3] ``Guide for Design of Substation Rigid Bus Structures'' Chapter 5 and Annex B ``Bus-Conductor Ampacity'' and Annex C ``Thermal Considerations for outdoor Bus Conductor Design.''

B. CONTINUOUS AND EMERGENCY RATINGS

Rigid bus ampacities currently used by Tri-State are based on the values found in Annex B of IEEE Std 605-1998, considering a temperature rise of 30 °C over ambient, with sun, and an Emissivity of 0.5. The formulas used are outlined in Annex B of [3] and the assumptions made are outlined in Annex C of [3]. Rigid bus current ratings are derived from calculating the convective and radiation heat losses of the bus and offsetting those losses by the heat gain by solar exposure, if applicable. Those formulas are dependent on the bus geometry (round tube, square, Integral web, etc.). For the purposes of this paper, the calculations considers round tube, aluminum and copper bus of various sizes as it used in most Tri-State installations.

The formula for calculating current rating is defined:

$$I = \sqrt{\frac{q_c + q_r - q_s}{R \cdot F}} \tag{6}$$

where

- $I =$ current for the allowable temperature rise, amps.
- $q_c =$ convective heat loss, watts/ft.
- $q_r =$ radiation loss, watts/ft.
- $q_s =$ solar heat gain, watts/ft.
- $R =$ direct current resistance at the operating temperature, ohms/ft.
- $F =$ skin effect coefficient for 60 cycle current.

For cylindrical surfaces, when there is a windspeed of 2 fps and 1 atmosphere of pressure, the convective heat losses are defined as:

$$q_c = 0.010 \cdot d^{-0.4} \cdot A \cdot \Delta T \tag{7}$$

where

- $d =$ diameter of the cylinder, inches
- $A =$ Surface area in^2/ft
- ΔT = Difference in temperature in $°C$ between conductor surface and ambient air temperature

Throughout the different equations used, different areas are assumed when measuring different heat losses or gains. In this instance, the surface area is considered as the external surface area of 1 foot (12 inches) of bus. Therefore, for cylindrical surfaces, $A = 12\pi d$. The radiation heat losses are calculated with different levels of emissivity, ε, which represent the amount of weathering on the bus. A value of 0.5 is typically used to represent heavily weathered aluminum which avoids needing to update the ratings as the bus ages.

$$q_r = 36.9 \times 10^{-12} \varepsilon A (T_c^4 - T_a^4) \tag{8}$$

where

- ε = emissivity corresponding to the temperatures of interest. Here is assumed emissivity at T_c equals absorptivity of energy spectrum at T_a. This is usually a good approximation.
- $T_c =$ temperature of conductor, Kelvin
- $T_a =$ temperature of surrounding bodies, Kelvin
- $q_r =$ radiation loss watts/linear foot

The Area used in radiation losses is also the external surface area of 1 foot (12 inches) of bus. Finally, when calculating daytime ratings, the impact of solar heating is considered. The tables used in Annex B make the following assumptions on the location and orientation of the bus:

Elevation: 0 ft
Latitude: 30° North
Time of Day: Noon
Bus Orientation: N-S
Atmosphere: Clear

Additionally, the area calculated is the area which projects a shadow over a 12 inch section of bus, which for a cylinder would be equal to $A_s = 12d$.

$$q_s = 0.00695 \varepsilon_s Q_s A_s K \sin(\theta) \tag{9}$$

where

- $\varepsilon_s =$ coefficient of solar absorption, usually somewhat higher than emittance, but generally taken as equal to that used for radiation loss
- $\theta =$ effective angle of incidence of sun:

$$\cos^{-1}[\cos(H_c)\cos(Z_c - Z_l)] \tag{10}$$

- $q_s =$ solar heat gain in watts/linear foot
- $H_c =$ altitude of sun, degrees
- $Z_c =$ azimuth of sun, degrees
- $Z_l =$ azimuth of conductor line, degrees (0 or 180 for N-S / 90 or 270 for E-W)
- $A_s =$ projected area of conductor, square inches per foot (area casting shadow)
- Q_s = total solar and sky radiated heat on a surface normal to sun's rays, watts/sq.ft
- $K =$ heat multiplying factors for high altitudes

Typical values for variables for the calculation of the effective angle of incidence are located in Annex C, Table C.1 – Data for calculating solar heat gain.

The final components are the calculation of the resistance, R, and the skin effect factor, F. For Aluminum bus:

$$R = \frac{8.145 \times 10^{-4}}{C' A_2}\left[1 + \frac{0.00403\ C'}{61}(T_2 - 20)\right] \tag{11}$$

where

- $C' =$ conductivity as % IACS
- $A_2 =$ cross-sectional area, square inches
- $T_2 =$ conductor temperature, $°C$

For Copper bus, the same formula is adapted to account for its conductivity:

$$R = \frac{8.145 \times 10^{-4}}{C' A_2}\left[1 + \frac{0.00393\ C'}{100}(T_2 - 20)\right] \tag{12}$$

The cross-sectional area of the conductor for a cylindrical tube is defined as

$$A = \pi\left(\left(\frac{d_{OD}}{2}\right)^2 - \left(\frac{d_{ID}}{2}\right)^2\right). \tag{13}$$

The conductivity data is provided by the Aluminum Electrical Conductor Handbook [2], with typical values of 53% IACS. The skin effect factor changes as temperature increases and is different for every size and geometry of rigid bus. The Aluminum Electrical Conductor Handbook provides F, also labeled as $\frac{R_{ac}}{R_{dc}}$ at 70°C. Specifications for copper bus conductors were provided in ASTM B-188 [7] "Standard Specification for Seamless Copper Bus Pipe and Tube" for the skin effect factor, and the IEEE standard lists typical conductivity 99% IACS and emissivity ($\varepsilon = 0.85$) for copper.

AAR calculations for a rigid bus should assume a constant maximum conductor temperature; 70°C for Normal Ratings, 100°C for Long Term Emergency Ratings, and 110°C for Short Term Emergency Ratings. As such, for every degree that ambient temperature is lowered in the equations, one degree should be added to the allowable temperature rise of the bus.

Though the above information may be used to derive a set of standard ambient adjusted ampacities of rigid bus, each utility should consider, based on the geographic distribution of their facilities, whether additional sets of ratings are required to account for location based variables in the equations.

IV. CIRCUIT BREAKER RATINGS

A. GENERAL ASSUMPTIONS

Determination of ratings for Circuit Breakers that are not enclosed (i.e. non-Metalclad breakers) are covered by IEEE C37.10-2016 [8] "Application Guide for AC High-Voltage Circuit Breakers > 1000 Vac Rated on a Symmetrical Current Basis" and IEEE C37.04-2018 [13] "Standard for Ratings and Requirements for AC High-Voltage Circuit Breakers with Rated Maximum Voltage Above 1000 V". Circuit breaker ratings are determined based on the individual maximum temperature limits of the materials used for the construction of the breakers.

These ratings make initial assumptions of an ambient temperature of 40 C and use known material maximum temperatures as identified in Table 1 of IEEE C37.04. Then, using formulas provided in IEEE C37.10 and the previously identified maximum temperatures, the rated ampacities can be scaled to derive new ratings.

In general, a smaller allowable maximum temperature results in more conservative ratings as temperatures increase, and a larger allowable maximum temperature results in more conservative ratings as temperatures decrease. A range of maximum allowable temperature rises over ambient has been established based on the various components typically used in the construction of the circuit breakers. From Table 1 of IEEE C37.04, a review of the current carrying components (1,2,3 and 5) provides a range of allowable temperature rises over ambient from 50 C to 75 C.

Therefore, for establishing ratings in higher-than-rated ambient temperatures, 50C will be used as the maximum temperature rise, and 75C will be used in establishing ratings for lower-than-rated ambient temperatures. Exceptions may be applied on a case-by-case basis.

B. CONTINUOUS RATINGS

For continuous current on a non-enclosed circuit breaker, IEEE 37.10, section 4.5.3.2, provides the following formula to derive the adjustments to the rated current, I_r, for changes in the ambient temperature.

$$I_a = I_r \left[\frac{\theta_{max} - \theta_a}{\Delta\theta_r} \right]^{1/1.8} \tag{14}$$

where

- I_a is allowable continuous load current at the actual ambient temperature θ_a (I_a is not to exceed two times I_r) (A),
- I_r is rated continuous current (A),
- θ_{max} is allowable hot-spot total temperature ($\theta_{max} = \Delta\theta_r + 40°C$),
- θ_a is actual ambient temperature expected (between $-30°C$ and $60°C$),
- $\Delta\theta_r$ is allowable hot-spot temperature rise at rated current ($°C$)

For each model, the maximum allowable temperature of the most limiting component needs to be determined. The data can then be applied as in the following example: Where, rated current = 3000A, and the maximum allowable temperature is 90C. For an ambient temperature of 30C, the new allowable current:

$$I_a = 3000 \left[\frac{90 - 30}{50} \right]^{1/1.8} = 3320 \text{ Amps} \tag{15}$$

C. EMERGENCY RATINGS

When Emergency ratings of a breaker have already been established, IEEE 37.10, 4.5.4.3 provides the methodology for adjusting the emergency ratings to actual ambient temperature. The calculation relies on the ambient adjustments to the continuous rating discussed in 4.1 of this document. The ambient adjusted emergency rating is as follows:

$$I_{ea} = I_r \left[\left(\frac{I_a}{I_r} \right)^{1.8} + \left(\frac{I_e}{I_r} \right)^{1.8} - 1 \right]^{1/1.8} \tag{16}$$

where

- I_a is allowable continuous load current at the actual ambient temperature
- I_{ea} is allowable emergency load current at the actual ambient temperature
- I_e is the emergency load current at $40°C$ ambient temperature
- I_r is the continuous load current at $40°C$ ambient temperature

Continuing the previous example, where the ambient adjusted continuous rating was determined to be 3320 Amps, if the emergency rating at 40C is 3500 Amps, then the ambient adjusted emergency rating is calculated as:

$$\begin{aligned} I_{ea} &= 3000 \left[\left(\frac{3320}{3000} \right)^{1.8} + \left(\frac{3500}{3000} \right)^{1.8} - 1 \right]^{1/1.8} \\ &= 3785 \text{ Amps} \end{aligned} \tag{17}$$

The following formulas can be applied to create a table of scaling factors using the individual utility's emergency rating criteria.

V. CIRCUIT SWITCHER RATINGS

IEEE C37.016 [12], titled "Standard for High Voltage Circuit Switchers Rated 15.5kV through 245kV," in Section 5.5 on Rated Continuous Current, directly references subclause 5.5 of IEEE C37.100.1-2018 [11].

In IEEE C37.100.1-2018, titled "Standard for Common Requirements for High-Voltage Power Switchgear rated above 1000V," subclause 5.5 presents an identical maximum temperature rise table of components as that of the circuit breaker. Subclause 5.5.2 indicates that at lower ambient temperatures, a higher loading may be assigned to the device and refers to IEEE C37.010 [8] for guidance on calculating the rating.

IEEE C37.010 is the standard which is the basis for Circuit Breakers ratings. Therefore, we can treat Circuit Switchers as Circuit Breakers from a rating perspective, and as the maximum temperature table is the same, utilize the very same recommendations.

VI. LINE TRAP RATINGS

A. GENERAL ASSUMPTIONS

Ratings for Line Traps are determined based on the requirements of IEEE 93.3-2017 [10] "Requirements for Power-Line Carrier Line Traps". The standard however, provides little information on adjusting existing ratings due to changing ambient temperatures. Section IV-B of the standard states that "the allowable temperature rise shall be reduced by the same number of degrees the ambient temperature exceeds the upper temperature limit" in the event that the ambient temperatures exceed certain maximums and time components. The standard however does not directly provide factors for the scaling of the ratings. The standard provides greater guidance in the calculation of the emergency ratings for line traps. As the calculation of the emergency ratings is comparable to an adjustment to the maximum allowable temperature, with a built-in time component, we will use the formula for the calculation of the emergency ratings to derive the adjustments required for ambient ratings. In regard to adjustments to line trap ratings due to solar irradiance, no guidance is provided in any existing standard or paper on addressing the additional temperature increase. Due to unavailable line trap identification data for certain older models of traps, the recommendation is to utilize separate maximum allowable temperatures for determining the increase and decrease in rating such that the most conservative rating changes are utilized. A review of installed Tri-state line-traps has identified a range of maximum allowable temperature rises over ambient from 140 C (Trench class H) to 90 C (GE CF Type before 1965) as provided by IEE C93.3 Table A.2. Therefore, for establishing ratings in higher-than-rated ambient temperatures, 90C will be used as the maximum temperature rise, and 140C will be used in establishing ratings for lower-than-rated ambient temperatures. Exceptions may be applied on a case-by-case basis.

B. CONTINUOUS RATINGS

Appendix A of IEEE 93.3 discusses the calculation of emergency rating temperature rise as follows:

$$\theta_{ER} = \left[\left(\frac{I_{ER}}{I_{NR}} \right)^2 - 1 \right] \times [\theta_{NR}] \times \left[1 - e^{-\left(\frac{t_{ER}}{\tau}\right)} \right] \quad (18)$$

where:

- θ_{ER} is the rise in temperature above the normal rating
- θ_{NR} is the limit of observable temperature rise at rated continuous current (As found in IEEE C93.3 Table A.2)
- I_{ER} is the emergency overload current: the desired emergency overload current
- I_{NR} is the normal continuous current: the rated continuous current
- t_{ER} is the duration of emergency rating: the length of time of the emergency period in minutes
- τ is (tau) thermal time constant of the winding in minutes. This is 48 min for encapsulated coils and 15 min for open style coils

If we consider increasing (or decreasing) ambient temperature as additional rise (or decrease) in temperature above the normal rating, then we can replace θ_{ER} with $40 - \theta_a$ and as a consequence I_{ER} with I_{ar}, the ambient adjusted current. Further, in order to calculate the continuous rating, instead of an emergency rating, we can set t_{ER} to a large number, which will reduce the final factor of the equation to 1. This results in the following formula:

$$40 - \theta_a = \left[\left(\frac{I_{ar}}{I_r} \right)^2 - 1 \right] \theta_r \quad (19)$$

where:

- θ_a is the actual ambient temperature
- θ_r is the maximum allowable temperature rise over ambient
- I_{ar} is the continuous current at actual ambient temperature
- I_r is the continuous current at 40°C

Re-arranging the equation to solve for I_{ar}:

$$\frac{40 - \theta_a}{\theta_r} + 1 = \left(\frac{I_{ar}}{I_r} \right)^2 \quad \rightarrow \quad I_{ar} = I_r \sqrt{\frac{40 - \theta_a + \theta_r}{\theta_r}} \quad (20)$$

where $40 + \theta_r = \theta_{max}$, the maximum allowable temperature of the component. Therefore:

$$I_{ar} = I_r \sqrt{\frac{\theta_{max} - \theta_a}{\theta_r}} \quad (21)$$

The resultant formula is in line with other derivation performed in implementation documents of other entities (see PJM Guide for determination of Line Trap Ratings [4]) and with the formulas for other equipment types whose ratings are primarily dependent on the temperature rise of a most limiting part/metal such as circuit breaker and switches.

C. EMERGENCY RATINGS

The standard does not immediately call out the adjustment to the emergency rating of the line trap as a function of changing ambient temperature. However, this too can be derived if the current emergency rating is known, as the time constant and duration of the emergency rating can be treated as constant. Taking the same formula A.2 in the Annex 2 of IEEE 93.3, we can write out two equations, one for the normal emergency rating, and one for the ambient adjusted emergency rating:

Emergency Rating:

$$\theta_E = \left[\left(\frac{I_E}{I_r}\right)^2 - 1\right]\theta_r\left(1 - e^{-\frac{t}{\tau}}\right) \tag{22}$$

Ambient Adjusted Emergency Rating:

$$\theta_E = \left[\left(\frac{I_{AE}}{I_a}\right)^2 - 1\right]\left(\theta_{Max,r} - \theta_a\right)\left(1 - e^{-\frac{t}{\tau}}\right) \tag{23}$$

where,

- θ_E is the maximum allowable emergency temperature rise over θ_r
- θ_r is the maximum allowable temperature rise over ambient
- θ_a is the actual ambient temperature
- $\theta_{Max,r}$ is the maximum allowable temperature rise of the line trap
- I_a is the continuous current at actual ambient temperature
- I_r is the continuous current at 40°C
- I_{AE} is the ambient adjusted emergency current
- I_E is the emergency current at 40°C
- t is the duration of the emergency rating (minutes)
- τ is the time constant of the trap

In both formulas θ_E is the same as it is the thermal limit which defines the emergency rating. The ambient adjusted formula has been modified such that the temperature rise over ambient θ_r is no longer based on $40°C$ but on the actual ambient temperature. As a result, the current in the denominator also needs to be modified to represent the ambient adjusted continuous current. Therefore if we want to establish a relationship between the existing emergency ratings and the ambient adjusted emergency ratings, we can set the right-hand side of the equations equal to each other as θ_E is the same in both equations:

$$\left[\left(\frac{I_E}{I_r}\right)^2 - 1\right]\theta_r\left(1 - e^{-\frac{t}{\tau}}\right) = \left[\left(\frac{I_{AE}}{I_a}\right)^2 - 1\right] \times \left(\theta_{Max,r} - \theta_a\right)\left(1 - e^{-\frac{t}{\tau}}\right) \tag{24}$$

We can remove the time-constant factor, as it appears on both sides:

$$\left[\left(\frac{I_E}{I_r}\right)^2 - 1\right]\theta_r = \left[\left(\frac{I_{AE}}{I_a}\right)^2 - 1\right]\left(\theta_{Max,r} - \theta_a\right) \tag{25}$$

If we move the θ_r factor to the other side, we see that this is equivalent to the continuous rating formula (20). So we can substitute and then solve for I_{AE}:

$$\left[\left(\frac{I_E}{I_r}\right)^2 - 1\right] = \left[\left(\frac{I_{AE}}{I_a}\right)^2 - 1\right]\left(\frac{\theta_{Max,r} - \theta_a}{\theta_r}\right) \tag{26}$$

$$\left[\left(\frac{I_E}{I_r}\right)^2 - 1\right] = \left[\left(\frac{I_{AE}}{I_a}\right)^2 - 1\right]\left(\frac{I_a}{I_r}\right)^2 \tag{27}$$

$$\left(\frac{I_E}{I_r}\right)^2 - 1 = \left(\frac{I_{AE}}{I_r}\right)^2 - \left(\frac{I_a}{I_r}\right)^2 \tag{28}$$

$$I_{AE} = I_r\sqrt{\left(\frac{I_a}{I_r}\right)^2 + \left(\frac{I_E}{I_r}\right)^2 - 1} \tag{29}$$

This formula is again equivalent to the formulas for the calculation of ambient adjusted emergency ratings for other equipment types whose ratings are primarily dependent on the temperature rise of a most limiting part/metal such as circuit breaker and switches. The following formulas can be applied to create a table of scaling factors using the individual utility's emergency rating criteria.

VII. DISCONNECT SWITCH RATINGS

A. GENERAL ASSUMPTIONS

Ratings for switches are determined based on the requirements of IEEE C37.30.1-2011 [6] "Requirements for AC High-Voltage Air Switches rated above 1000V". The standard, similar to the discussion on Line Traps and Circuit breakers, presents a table with various temperature rise limits for different components of the switch. The most limiting of those temperatures, based on the individual switch construction is to be applied to the formulas discussed below. The standard clearly outlines the process for adjusting continuous and emergency ratings of switches in the sections presented below. A range of maximum allowable temperature rises over ambient has been established based on the various components typically used in the construction of the disconnect. Therefore, for establishing ratings in higher-than-rated ambient temperatures, 75C will be used as the maximum temperature, and 105C will be used in establishing ratings for lower-than-rated ambient temperatures. Exceptions may be applied on a case-by-case basis.

B. CONTINUOUS RATINGS

Section 5.4 "Rated Continuous Current" of IEEE 37.30.1 discusses the calculation of rating scaling factors, called Loadability Factors (LF) that are used to correct rated currents for the actual ambient temperature. The formulas provided are similar to the ones observed for other devices:

$$I_a = I_r\left(\frac{\theta_{max} - \theta_a}{\theta_r}\right)^{0.5} \tag{30}$$

where

- θ_a is ambient temperature (°C)
- I_a is allowable continuous current at ambient temperature, θ_a
- I_r is rated continuous current
- θ_{max} is allowable maximum temperature (°C) of switch part, from IEEE C37.30 Table 3
- θ_r is limit of observable temperature rise (°C) at rated current of switch part, from IEEE C37.30 Table 3

Unlike other devices, in IEEE C37.30.1 θ_r does not refer to $\theta_{max} - \theta_a$, rather it refers to an adjusted value such that at 25°C the rated current is 1.22% of the normal 40°C based rating. The adjustment for θ_r in the standard is calculated as follows:

For non-enclosed switches,

$$\theta_r = \frac{\theta_{max} - \theta_n}{1.5} \tag{31}$$

For enclosed switches, the lesser of

$$\theta_r = \frac{\theta_{max} - \theta_{el}}{1.5} \quad \text{or} \quad \theta_r = \theta_{max} - \theta_{e2} \tag{32}$$

where

- θ_n is 25°C, the standard ambient temperature
- θ_{el} is 40°C
- θ_{e2} is 55°C
- 1.5=$(1.22)^2$, where 1.22 is loadability of switch at θ_n

However, calculating θ_r as in (28) and (29) for $40°C$ ambient temperature, yields a rating that is no longer 100% due to the fixed $1.5(1.22\%)^2$ factor that is applied. Therefore, given the more conservative range of θ_{max} values we are applying to the calculations, normal ratings are to be determined based on the more traditional $40°C$ rating where $\theta_r = \theta_{max} - 40°C$.

C. EMERGENCY RATINGS

Annex C of IEEE C37.30.1 contains the straightforward formulations for the adjustment of the emergency ratings due to varying ambient temperatures. The formulations provided maintain the same adjusted factors for the maximum allowable temperature rise as discussed above. The emergency ratings for disconnect switches are based on an additional 20 degree temperature allowance for ratings less than 24 hours. However, when applying different maximum allowable temperature limits for ratings above or below the rated temperature, maintaining an additional 20 degree rise allowance creates a step change in ratings when ambient temperature is above rated temperature. Therefore, to maintain a more consistent rating profile, the allowable temperature rise for emergency ratings is decreased to 10 degrees when using the 75C maximum temperature. For ambient temperatures greater than 125F, 30 minute and 4 hours emergency ratings are set to 100% of the rated continuous current, as long as the corresponding additional temperature does not exceed the 20 degrees set forth by the standard.

For the ambient temperatures greater than 125°F, the implications of setting 30-minute and 4-hour emergency ratings to 100% of the rated continuous current are minimal. Most of the United States and most countries have never once experienced ambient temperatures greater than 125°F; and the odds of experiencing this temperature while simultaneously experiencing system conditions permitting the use of emergency ratings is extremely small. In addition, for temperatures up through 135°F, the additional temperature allowance implied by this approach does not exceed the 20°C permitted by the standard.

$$LE_1 = \sqrt{\frac{\theta_{max} + \Delta\theta_{e1} - \theta_r(e^{-\frac{d}{T}}) - \theta_A}{\theta_r(1 - e^{-\frac{d}{T}})}} \leq 2.0 \tag{33}$$

(for a duration less than 24 h)

$$LE_2 = \sqrt{\frac{\theta_{max} + \Delta\theta_{e2} - \theta_A}{\theta_r}} \leq 2.0 \tag{34}$$

(for a duration more than 24 hr)

where

- LE_1 is the ratio of emergency load current capability to rated continuous current for duration of less than 24 h
- LE_2 is the ratio of emergency load current capability to rated continuous current for duration of more than 24 h
- θ_{max} is allowable maximum temperature (°C) when carrying rated continuous current
- $\Delta\theta_{e1}$ is additional temperature, 20 °C, allowed during emergency conditions for durations less than 24 h
- $\Delta\theta_{e2}$ is additional temperature, 10 °C, allowed during emergency conditions for durations more than 24 h
- θ_r is the limit of observable temperature rise (°C) at rated continuous current (actual temperature rise data may be used)
- θ_A is ambient temperature (°C) for nonenclosed switches or external ambient temperature for enclosed switches; for enclosed switches only, add 15 °C to external ambient temperature in Equation (32) and Equation (33) to realistically represent cooling air temperature inside enclosure
- T is the thermal time constant (min) (generally 30 min for switches)
- d is the duration of emergency (min)

The 30-minute and 4-hour emergency ratings that Tri-state employs for disconnect switches are based on the 45 degree ambient temperature rating as calculated in the tables of Annex C. However, the ratings of the Annex C calculations are based on the adjusted rating as discussed in the continuous rating section. In a similar fashion, the application of the ambient adjusted ratings would create a mismatch in the emergency ratings when the ambient temperature is increased to the original $40°C$ rating. Therefore, the scaling factors

TABLE 3. Sample range of AARs for select facility types over a temperature range of −30F to 130F, as % of existing rating.

Equipment Type	Ambient Adjusted Rating (AAR)	Short Term Emergency AAR	Long Term Emergency AAR	Notes
Transformers (OFAF, 30C Normal Rating)	66-148%	87-110%	93-105%	Ratings vary based on ambient temperature and cooling methods (ONAN, ONAF). Emergency ratings assume short-term overload conditions.
Rigid Bus-Conductors (Round, Sched 40 Aluminum, 3 inch, 5000ft a.s.l, with Sun, 30C Normal Rating)	27-177%	81-133%	76-139%	Dependent on ambient conditions like temperature and solar radiation. Emergency conditions consider higher temperature tolerance.
Circuit Breakers (40C Normal Rating)	83-147%	88-136%	86-140%	Adjustments made for ambient temperatures ranging from -30°C to 60°C. Emergency ratings consider short-duration high-current capability.
Circuit Switchers (40C Normal Rating)	83-147%	88-136%	86-140%	Similar considerations as circuit breakers, adjusted for actual ambient temperature. Emergency ratings are based on short-term capacity.
Line Traps (40C Normal Rating, LTE = Normal Rating)	84-141%	90-125%	84-141%	Includes considerations for solar irradiance and higher ambient temperatures. Emergency ratings factor in short-term overload conditions.
Disconnect Switches (40C Normal Rating)	76-146%	82-148%	82-128%	Includes emergency ratings adjustments based on higher ambient temperatures.
Current Transformers (CTs rated for 55C rise of 30C ambient)	75-147%	N/A	N/A	RF adjustments based on ambient temperature up to 30°C. Emergency ratings consider higher short-term load capacity.

for ambient adjusted ratings should be computed using the original $40°C$ rating, such that $\theta_r = \theta_{max} - 40°C$, and the appropriate allowable temperature rise.

VIII. CURRENT TRANSFORMER RATINGS

A. SEPARATELY MOUNTED CURRENT TRANSFORMERS

Current Transformers that are not mounted in transformer or circuit breaker bushings are typically assigned a Rating Factor (RF) that is used in determining its normal rating. IEEE C57.13-2016 [9] "Requirements for Instrument Transformers" section 4.4.2 states that the same RF can be used to determine a new rating factor at other-than $30°C$ ambient temperatures. The only additional data required is the rated temperature rise over ambient. Typical values are listed in Table 4 of the standard as $55°C$, $65°C$, or $80°C$ rise over $30°C$ ambient or $30°C$, $40°C$ or $55°C$ rise over $55°C$ ambient. CTs with a $55°C$ rise of $30°C$ ambient are most prevalent in the Tri-state system and thus it will be used as the basis for the recommendations.

The direct formula for determining the new rating factor is not provided in the standard, however, the GE "Instrument Transformer Basic Technical Information and Application" guide [1] lists the relationship as presented in this document, which aligns to the graphical results presented in Figure 1 of IEEE C57.13.

$$RF_{aa} = RF_r\sqrt{\frac{\theta_{max} - \theta_a}{\theta_r}} \text{ where,} \tag{35}$$

- θ_{max} is the total rated temperature rise plus rated ambient temperature
- θ_r is the total rated temperature rise
- θ_a is the new ambient temperature
- RF_r is the rating factor at the rated ambient temperature
- RF_{aa} is the rating factor at the adjusted ambient temperature, not to exceed 2x RF_r

To get the final rating, the RF of the CT is multiplied by the selected tap of the CT.

IEEE standards and manufacturer documentation do not provide for long term (i.e., greater than 1s) emergency ratings for Current Transformers, therefore no emergency ratings shall be applicable for Stand-alone or Bushing Mounted CTs.

B. BUSHING-TYPE CURRENT TRANSFORMERS

IEEE C57.13 Annex B details the different requirements and operating conditions of bushing type CTs. Differently from separately mounted CTs, bushing CTs (BCTs) are typically located in enclosed environments, either externally or internal to equipment, typically circuit breakers and power transformers. Bushing CTs may be submerged in oil, or they may be located in air pockets/turrets above the oil. Though Annex B outlines the various typical operating temperatures for the BCTs, when it comes to changing the rating factor due to changes in ambient temperature, section B.4.4 refers the user to the manufacturer:

"The use of the de-rating chart... is not applicable for BCTs. In the case of lower ambient temperatures it should not be assumed that the RF can increase. Such considerations shall be discussed with the BCT manufacturer."

However, if even greater accuracy is required in estimating the temperatures of the BCTs, and after the manufacturer has been consulted, advanced thermal modeling techniques can be used to simulate the internal environment of a circuit breaker or transformer, providing a more dynamic assessment of BCT thermal stress. While manufacturer consultation remains crucial, integrating such predictive modeling tools could enhance the precision of rating adjustments in response to changes in the operating environment. Such modeling is outside of the scope of this paper, but could serve as a basis for the development of future standards.

Tri-State Circuit Breaker BCTs are of the slip-over style, mounted around the bushing. These CTs are exposed to the same ambient conditions as the separately mounted CTs. As such, these CTs shall be rated following the same methodology. This same would apply to slip-over style BCTs applied on transformers.

The ambient temperature of the space surrounding the BCTs that are located inside the transformer tank, or in a turret above the transformer tank, are more difficult to determine. Unless separately measured, the temperature within that space is not only impacted by the surrounding ambient temperature, but also by the temperature inside the transformer. A transformer loaded at 30% of its rating vs a transformer loaded at 70% of its rating, though they both experience the same external ambient temperature, will have different internal temperatures, therefore the ambient temperature surrounding the BCT will be different. Further, as the ratings of the transformer are already adjusted for ambient temperature, with the goal of maintaining the same hottest-spot temperature, the ambient temperature of the CT should never exceed its rated values, nor can it be confirmed that the temperature has decreased to the point of allowing an increase in its rating factor. Therefore, the rating of BCTs should be assumed to remain constant.

IX. CONCLUSION

This paper presents the methodology, equations and required information found in industry standards to calculate AARs for various substation equipment based on varying ambient temperatures and, where applicable, solar heating. This data has been used to develop factors for scaling normal/emergency ratings that can be applied to various types of equipment as a means of implementing the requirements of FERC Order 881.

With the exception of transformers and bus-conductors, standards identified the temperature tolerances of the materials used in the device construction as the main consideration when calculating adjustments to nominal. Using tables provided in the standards and manufacturer specifications, it was possible to create conservative guidelines for adjusting the ratings by selecting the most conservative maximum temperature limits for each device.

As a reference, Table 3 shows sample ranges of AArs for select facility types over a Temperature Range of -30F to 130F, as % of MVA rating or % of existing emergency ratio. The above ranges of rating changes are based on specific sample scenarios, as such, they should not be assumed to represent all possible conditions or equipment. They are provided for illustrative purposes only. However, this table shows the breadth of possible ranges, illustrating the need for facilities operators to indeed perform the calculations described in this paper.

Standards for transformer ratings provide tables for increasing/decreasing ratings based on ambient temperature adjustments. However, application of the formulas to test data from a variety of in-service transformers leads to recommendations that provide for more conservative rating than those provided in the standards. Finally, given the greater number of variables that comprise the calculation of bus-conductors, the paper does not provide a methodology for calculating rating changes of rigid bus. Rather, the formulas discussed in the standards have been provided along with the assumptions in the standard required to create the appropriate tables.

One of the most significant outcomes of the study is the development of conservative equipment rating scaling factors. These factors are designed to be applied universally across a utility's fleet, ensuring consistent and reliable operation even in the absence of detailed equipment-specific data. By applying the proposed AAR methodology to actual equipment data, our work demonstrates practical applicability and scalability of the suggested methodology. The findings suggest that utilities can adopt this approach to optimize transmission capacity, and reduce the risk of equipment failure due to overloading.

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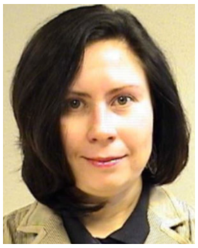

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