DYNAMIC LINE RATING USING THE
HIGH RESOLUTION RAPID REFRESH
(HRRR) MODEL


8 November 2017
Agenda

• Line rating background
• The case for additional capacity
• Sensitivity analysis of line ratings
• Using the HRRR in line ratings
Line Rating Background

- Conductor temperatures are a function of:
  
  1. Conductor material properties (primarily electrical conductivity and heat capacity for non-steady state)
  2. Conductor diameter
  3. Conductor surface condition (primarily emissivity and absorptivity)
  4. Weather conditions (air temperature, solar heating, wind speed and direction)
  5. Conductor electrical current

Adapted from IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors, IEEE Power and Energy Society, 2013
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Line Rating Background

• Three cases for conductor temperatures:
  1. Steady State Case – current, weather, and conductor temperature constant
  2. Transient Case – weather is constant, current undergoes a step change that leads to a new conductor temperature over some time
  3. Dynamic Case – weather and current vary over time affecting the conductor temperature

Steady state heat balance equation

\[ I = \sqrt{\frac{q_c + q_r - q_s}{R(T_c)}} \]

Non-steady state heat balance equation

\[ \frac{dT_c}{dt} = \frac{1}{m \cdot C_p} [R(T_c) \cdot I^2 + q_s - q_c - q_r] \]

Adapted from IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors, IEEE Power and Energy Society, 2013
Using the Line Rating Equations

- At the maximum allowable conductor temperature
  \[
  \frac{dT_c}{dt} = 0
  \]

- This allows for the maximum current to be passed through the line without raising the temperature

- Solving the non-steady state heat balance equation for this condition
  \[
  \frac{dT_c}{dt} = \frac{1}{m \cdot C_p} [R(T_c) \cdot I^2 + q_s - q_c - q_r]
  \]
  \[
  0 = \frac{1}{m \cdot C_p} [R(T_c) \cdot I^2 + q_s - q_c - q_r]
  \]
  \[
  I = \sqrt{\frac{q_c + q_r - q_s}{R(T_c)}} \quad \text{Steady state equation}
  \]

Adapted from IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors, IEEE Power and Energy Society, 2013
Equations

• In order to solve the steady state equation, we need:
Equations

- In order to solve the steady state equation, we need:

\[
q_{c1} = K_{angle} \cdot \left[1.01 + 1.35 \cdot N_{Re}^{0.52}\right] \cdot k_f \cdot (T_s - T_a)
\]

\[
q_{c2} = K_{angle} \cdot 0.754 \cdot N_{Re}^{0.6} \cdot k_f \cdot (T_s - T_a)
\]

\[
q_{cn} = 3.645 \cdot \rho_f^{0.5} \cdot D_0^{0.75} \cdot (T_s - T_a)^{1.25}
\]

\[
N_{Re} = \frac{D_0 \cdot \rho_f \cdot V_w}{\mu_f}
\]

\[
k_f = 2.424 \cdot 10^{-2} + 7.477 \cdot 10^{-5} \cdot T_{film} - 4.407 \cdot 10^{-9} \cdot T_{film}^2
\]

\[
T_{film} = \frac{T_s + T_a}{2}
\]

\[
K_{angle} = 1.194 - \cos(\phi) + 0.194 \cdot \cos(2\phi) + 0.368 \cdot \sin(2\phi)
\]

\[
\rho_f = \frac{1.293 - 1.525 \cdot 10^{-4} \cdot H_e + 6.379 \cdot 10^{-9} \cdot H_e^2}{1 + 0.00367 \cdot T_{film}}
\]

\[
\mu_f = \frac{1.458 \cdot 10^{-6} \cdot (T_{film} + 273)^{1.5}}{T_{film} + 383.4}
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\[
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\[ q_s = \alpha \cdot Q_{se} \cdot \sin(\theta) \cdot A' \]

\[ \theta = \arccos \left[ \cos \left( H_e \right) \cdot \cos \left( Z_e - Z_i \right) \right] \]

\[ \delta = 23.46 \cdot \sin \left[ \frac{284 + N}{365} \cdot 360 \right] \]

\[ H_e = \arcsin \left[ \cos(Lat) \cdot \cos(\delta) \cdot \cos(\omega) + \sin(Lat) \cdot \sin(\delta) \right] \]

\[ Z_e = C + \arctan(\chi) \]

\[ \chi = \frac{\sin(\omega)}{\sin(Lat) \cdot \cos(\omega) - \cos(Lat) \cdot \tan(\delta)} \]
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Now to Solve Those Equations ...

- We need:
  1. Properties of the transmission line
  2. Weather conditions
     - Traditionally based on seasonal worst-case conditions
       - High temperature, low wind, full sun
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Sample values from IEEE standard
Now to Solve Those Equations ...

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Sample values from IEEE standard

Values used by Kansas City Power & Light Company

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient air temperature (Summer) (°C/°F)</td>
<td>40 / 104</td>
</tr>
<tr>
<td>Ambient air temperature (Winter) (°C/°F)</td>
<td>10 / 50</td>
</tr>
<tr>
<td>Transmission Line Wind Speed (fps/mps)</td>
<td>4.0 / 1.22</td>
</tr>
<tr>
<td>Substation Conductor Wind Speed (fps/mps)</td>
<td>2.0 / 0.6</td>
</tr>
<tr>
<td>Wind Direction</td>
<td>Perpendicular to conductor axis</td>
</tr>
<tr>
<td>Line Orientation</td>
<td>East-West</td>
</tr>
<tr>
<td>Time of Day</td>
<td>12:00 pm</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>Clear</td>
</tr>
<tr>
<td>Absorptivity</td>
<td>0.5</td>
</tr>
<tr>
<td>Emissivity</td>
<td>0.5</td>
</tr>
<tr>
<td>Date</td>
<td>June 15</td>
</tr>
<tr>
<td>Time</td>
<td>12:00 Noon</td>
</tr>
<tr>
<td>Latitude</td>
<td>38.5° N</td>
</tr>
<tr>
<td>Longitude</td>
<td>94.0° W</td>
</tr>
<tr>
<td>Inclination Angle</td>
<td>0°</td>
</tr>
<tr>
<td>Ambient Air Temperature</td>
<td>37.7°C</td>
</tr>
<tr>
<td>Temperature</td>
<td>100°F</td>
</tr>
<tr>
<td>Line Axis Azimuth</td>
<td>90°</td>
</tr>
<tr>
<td>Elevation</td>
<td>950 feet</td>
</tr>
<tr>
<td>Absorptivity</td>
<td>1.0</td>
</tr>
<tr>
<td>Emissivity</td>
<td>0.85</td>
</tr>
<tr>
<td>Wind Direction</td>
<td>180°</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>2 ft/sec</td>
</tr>
</tbody>
</table>

Adapted from BHC Facility Rating Methodology, 2012

Adapted from Kansas City Power & Light Company Transmission Facility Rating Methodology, 2016
A Bunch of Numbers

Constants used:

**Conductor properties**
(e.g. Drake ACSR)
Diameter D = 0.0281 m
Emissivity $\varepsilon = 0.8$
Absorptivity $\alpha = 0.8$
$R_{\text{high}} = 8.688 \times 10^{-5}$
$R_{\text{low}} = 7.283 \times 10^{-5}$
$T_{\text{high}} = 75^\circ C$
$T_{\text{low}} = 25^\circ C$
$T_{\text{c_max}} = 90^\circ C$

**Line properties**
Elevation = 1000 m
Line azimuth = 90°
Latitude = 43°N

Weather Conditions:

**Seasonal Rating Values**
Summer, Winter, Transition
- Temperature = 40°C, 18°C, 27°C
- Wind Speed = 0.6 m/s
- Wind Direction = 90° (parallel to line azimuth)
- Solar Flux = 1030 W/m², 850 W/m², 1000 W/m²

**Weather Stations**
45 weather stations located in southern Idaho
15-minute time step observations of temperature, wind speed, wind direction, and solar flux
Used the daily minimum ampacity of the 45 weather stations
One Year of Line Ratings

Real-time line ratings based on the minimum daily ampacity value calculated using the observations from 45 weather stations in southern Idaho.

These conservative seasonal values are generally good, the real time ratings do not go lower than the seasonal values.

There is extra capacity between the seasonal rating and the real time rating. Dynamic line ratings could allow this capacity to be used.
One Year of Line Ratings

Real-time line ratings based on the minimum daily ampacity value calculated using the observations from 45 weather stations in southern Idaho.

Let’s zoom in on two cases and look at the line ratings at 15-minute time steps over one day:
One Year of Line Ratings

Real-time line ratings based on the minimum daily ampacity value calculated using the observations from 45 weather stations in southern Idaho.

Let’s zoom in on two cases and look at the line ratings at 15-minute time steps over one day:

1) Minimum daily rating well above the seasonal value
One Year of Line Ratings

Real-time line ratings based on the minimum daily ampacity value calculated using the observations from 45 weather stations in southern Idaho.

Let’s zoom in on two cases and look at the line ratings at 15-minute time steps over one day:
1) Minimum daily rating well above the seasonal value
2) Minimum daily rating at the seasonal value
On days where the daily minimum rating remained well above the seasonal rating, there was additional capacity available by adjusting ratings over smaller time scales.

The percent increase available in line rating varied between 22% and 95% throughout the day.
Variability Within a Minimum Day

On days where the daily minimum value lowered to the seasonal value, this only occurred for short periods and there was additional capacity during most of the day.

The percent increase available in line rating varied between 0% and 65% throughout the day.
Variability Within a Minimum Day

Conductor Line Rating - Minimum Among 45 Weather Station Observations at Each 15-Minute Time Step

Seasonal Rating
Real-time Rating

Hour (March 13, 2017)
Variability Within a Minimum Day

Conductor Line Rating - Minimum Among 45 Weather Station Observations at Each 15-Minute Time Step

<table>
<thead>
<tr>
<th>Station</th>
<th>Line Rating</th>
<th>Time</th>
<th>Temperature</th>
<th>Solar Flux</th>
<th>Wind Speed</th>
<th>Wind Direction</th>
<th>Perpendicular Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>#26</td>
<td>1047 A</td>
<td>1330L</td>
<td>61.15°F</td>
<td>716 W/m²</td>
<td>1.12 mph</td>
<td>137°</td>
<td>0.82 mph</td>
</tr>
<tr>
<td>#27</td>
<td>804 A</td>
<td>1415L</td>
<td>62.91°F</td>
<td>740 W/m²</td>
<td>1.04 mph</td>
<td>92°</td>
<td>0.04 mph</td>
</tr>
</tbody>
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Station #27

Line Rating 1047 A
Time 1330L
Temperature 61.15°F
Solar Flux 716 W/m²
Wind Speed 1.12 mph
Wind Direction 137°
Perpendicular Wind 0.82 mph

Station #26

Line Rating 804 A
Time 1415L
Temperature 62.91°F
Solar Flux 740 W/m²
Wind Speed 1.04 mph
Wind Direction 92°
Perpendicular Wind 0.04 mph
Question: Which environmental factor can we improve upon in the seasonal values?

Is this difference due to:
- Temperature?
- Winds?
- Solar flux?
Sensitivity Analysis

Wind speed has the greatest effect on line rating.
Sensitivity Analysis

Seasonal values are conservative

Seasonal Rating Values
(Summer, Winter, Transition)
Temperature = 40°C, 18°C, 27°C
Wind Speed = 0.6 m/s
Wind Direction = 90° (parallel to line azimuth)
Solar Flux = 1030 W/m², 850 W/m², 1000 W/m²
A parallel wind generates 60% less convective heat loss than a perpendicular wind.
Sensitivity Analysis

The line rating changes more rapidly at lower wind speeds.
How can we better account for future weather?

- Forecast!
- Persistence

2 types of persistence
1. General persistence - forecast the last known observed value to continue into the future

Current Time
1200Z

1300Z
1400Z
1500Z

Current temperature
73°F

1-hour persistence forecast = 73°F
2-hour persistence forecast = 73°F
3-hour persistence forecast = 73°F

11/14/17
How can we better account for weather?

- Forecast!
- Persistence

**2 types of persistence**
1. General persistence - forecast the last known observed value to continue into the future
2. 24-hour persistence - use the observed value from the previous day at the same time
Accuracy of Persistence Forecasts

Persistence forecasts are accurate in the short-term, but the errors quickly grow with time.
Accuracy of Persistence Forecasts

Persistence forecasts are accurate in the short-term, but the errors quickly grow with time.

Short-term persistence is better than 24-hour persistence (using value from previous day).
Can We Do Better Than Persistence?

• Forecast!
  • Persistence
  • Weather models

Forecast the last known observed value to persist into the future

Physics-based algorithms that use partial differential equations to predict the future state of the atmosphere.

High Resolution Rapid Refresh (HRRR)
What is the HRRR?

**Inputs**
Weather observations (temperature, wind, humidity, pressure)
Radar
Satellite

**HRRR**

**Processing:**
Partial differential equations
Parameterizations
Numerical approximations

**Outputs – Forecasts of:**
Temperature
Wind
Humidity
Rain
Clouds
Output of the HRRR

General Information

- Covers CONUS at 3 km horizontal grid spacing
- Forecasts produced ever hour with output from 0-18 hours into the future at 15-minute intervals

Used in this study

- Cut-out over Idaho with 3-km horizontal grid spacing
- Forecasts at 15-minute intervals from 2-18 hours
- Output variables of temperature, wind speed, wind direction, and solar flux
Applying HRRR Forecast Times to Operations

At 1230Z, you want to make a forecast for 1400Z

What is available?
1) 1100Z run of the HRRR, 3-Hour Forecast valid at 1400Z
2) Persistence from the most recent observation at 1230Z

Assumptions:
1) HRRR is available 80 minutes after its 0-Hour time
2) Observations from weather stations are available in real-time

Compare 3-Hour HRRR Forecast to 90-minute persistence forecast
Accuracy of HRRR Forecasts

RMSE of Temperature by Forecast Hour
HRRR Forecasts vs Observation Persistence

RMSE of Solar Flux by Forecast Hour
HRRR Forecasts vs Observation Persistence

RMSE of Wind Speed by Forecast Hour
HRRR Forecasts vs Observation Persistence

RMSE of Wind Direction by Forecast Hour
HRRR Forecasts vs Observation Persistence
Accuracy of HRRR Forecasts

Persistence is better than the HRRR at the 30-minute lead time
Accuracy of HRRR Forecasts

Persistence is better than the HRRR at the 30-minute lead time

Similar errors at 1.5 hour lead time (except wind direction)
Accuracy of HRRR Forecasts

Persistence is better than the HRRR at the 30-minute lead time

Similar errors at 1.5 hour lead time (except wind direction)

HRRR forecasts are more accurate than persistence for lead times 2.5 – 16.5 hours
How to Use HRRR Forecasts?

We know that there is some error in the HRRR forecast and we want to account for it to make our line ratings conservative.

*How do we do this?*

Threshold analysis of errors
- Given a HRRR forecast in a certain range, 98% of the weather station observations were found to be below (above) the threshold for temperature and flux (wind speed)
Error of HRRR Forecasts

- Conditional analysis at various thresholds for temperature, wind speed, and solar flux
- Used these values to modify the HRRR forecast and account for the potential error
  - For example, if the HRRR forecasted 103°F, then a value of 109.54°F was input into the line rating equation

<table>
<thead>
<tr>
<th>Given HRRR forecast of:</th>
<th>98% threshold of observations:</th>
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</thead>
<tbody>
<tr>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>&lt;20F</td>
<td>25.08F</td>
</tr>
<tr>
<td>20-49.9F</td>
<td>52.35F</td>
</tr>
<tr>
<td>50-69.9F</td>
<td>72.59F</td>
</tr>
<tr>
<td>70-89.9F</td>
<td>92.82F</td>
</tr>
<tr>
<td>90-99.9F</td>
<td>103.38F</td>
</tr>
<tr>
<td>&gt;100F</td>
<td>109.54F</td>
</tr>
<tr>
<td>Wind Speed</td>
<td></td>
</tr>
<tr>
<td>15-19.9 mph</td>
<td>2.56 mph</td>
</tr>
<tr>
<td>&gt;20 mph</td>
<td>2.83 mph</td>
</tr>
<tr>
<td>Solar Flux</td>
<td></td>
</tr>
<tr>
<td>5-19.9 W/m^2</td>
<td>35 W/m^2</td>
</tr>
<tr>
<td>20-99 W/m^2</td>
<td>280 W/m^2</td>
</tr>
<tr>
<td>100-299 W/m^2</td>
<td>438 W/m^2</td>
</tr>
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<td>300-499 W/m^2</td>
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<tr>
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<td>700-899 W/m^2</td>
<td>923 W/m^2</td>
</tr>
<tr>
<td>&gt;900 W/m^2</td>
<td>988 W/m^2</td>
</tr>
</tbody>
</table>
Line Rating with HRRR Forecasts

There are some times, particularly during the spring and summer, where using the HRRR forecast would have led to a lower line rating, which includes the safety factor.

This is the additional capacity in the lines that could have been gained over the last year by using HRRR 90-minute forecasts.
Percent Difference in Line Ratings with HRRR

Generally, 8% additional capacity September through February, then 5% additional capacity March through June. High temperatures during July and August prevented additional capacity during the summer.
The most frequent differences between HRRR forecast ratings and seasonal ratings were line rating increases of 0-15%.

~20% of days the minimum rating using the HRRR was below the seasonal rating (usually due to calm winds and seasonally high temperatures)
Can We Achieve Similar Results at Longer Lead Times?

Yes. The error of HRRR forecasts is similar across all leads times. This means that longer range forecasts can be used for line rating with similar results.
### Thresholds at Various Lead Times

<table>
<thead>
<tr>
<th>Given HRRR forecast of:</th>
<th>HRRR Forecast: 98% threshold of observations</th>
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</thead>
<tbody>
<tr>
<td></td>
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</tr>
<tr>
<td>Temperature</td>
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<td>&gt;20 mph</td>
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<td>Solar Flux</td>
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<td>933</td>
</tr>
<tr>
<td>&gt;900 W/m^2</td>
<td>988</td>
</tr>
</tbody>
</table>

The 98% thresholds change very little as forecast lead time increases.
Line Rating with HRRR 16-Hour Forecasts

Similar ratings to other HRRR forecast times.

In April 2018, the next version of the HRRR will produce operational forecasts out to 36 hours.
HRRR 90-minute forecasts would have increased the line rating from the seasonal value during the early part of the day (00-18Z) while decreasing the rating during a period (18-21Z) when the real-time rating approached the seasonal value.

Result = increased line rating and better safety margins
Conclusions

• Seasonal line ratings are conservative and line ratings could be raised by using forecasts from the HRRR
  • Weather forecasts add flexibility in operating and planning; additional time to decide how to operate efficiently
• Wind speed is the primary meteorological variable driving line ratings
• Additional work can be done to improve the thresholds and better account for specific line orientations and use cases

Contact: ken.fenton@noaa.gov