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ABSTRACT

Idaho National Laboratory and the Idaho Power Company, with collaboration from Idaho State University, have been working on a project to monitor wind and other environmental data parameters along certain electrical transmission corridors. The combination of both real-time historical weather and environmental data is being used to model, validate, and recommend possibilities for dynamic operations of the transmission lines for power and energy carrying capacity. The planned results can also be used to influence decisions about proposed design criteria for or upgrades to certain sections of the transmission lines.

1. INTRODUCTION

The addition of electricity from wind generation often places increased demands on associated power lines. A number U.S. policies and regulations have made the construction of new overhead power lines expensive and time consuming.[1,2] As an alternative, many electrical transmission system planners are exploring the possibility of increasing the capacity of existing transmission lines by maximizing the use of conductors already installed on towers.[3,4,5]

The current carrying capacity of a conductor is limited by its temperature, which is normally selected to maintain conductor strength and limit sag.

A common practice of electric utilities is to establish a static current rating for an overhead line based on average seasonal temperatures. A static rating for a line is determined from significant average temperature changes on a seasonal basis.

Weather conditions have a considerable effect on conductor temperatures. The weather provides cooling, principally by means of convective heat loss to the surrounding air. The degree of cooling thus depends on air temperature and wind velocity.[5] In the case of wind generation, the demand for increased current capacity in the transmission lines will correlate with high wind velocity. Under these conditions it may be possible to increase the current through the transmission line without exceeding maximum allowable conductor temperature.

Several technologies are used to determine the dynamic line ratings (DLR) of power transmissions lines. These can be grouped as weather based systems, conductor temperature monitoring systems, and tension-sag monitoring systems. The advantages and disadvantages of different dynamic line rating systems are described in Section 2.

2. METHODS FOR RATING TRANSMISSION LINES

Many methods have been used or attempted over the years to calculate static and dynamic ratings for transmission lines. DLR is a complex process because of the number of variables in the equations and the challenge of gathering and measuring enough data on enough of these variables to accurately calculate line capacity without large error bars.

Some of these systems include line sag and temperature monitors, line tension monitors, systems to mimic line conditions, and weather effects. The concern with almost all of these systems is that they typically do not take enough measurements along long lengths of transmission lines to get an accurate assessment of the varying climate conditions, line temperatures, and sags along each span. More weather data (wind speed, wind direction, ambient temperature, and solar irradiance) is needed along the transmission lines to improve the calculations and accuracy of existing systems.

Another way to improve existing systems would be to add more conductor sag, conductor tension, and conductor temperature monitoring devices along transmission lines, but these systems are typically too expensive to implement because they require many instruments in order to improve the error bands to acceptable levels. The installation of such devices often requires line outages, and cannot always be performed with the line energized, which can be costly and more challenging to coordinate for safety and other considerations.

Line tension monitoring systems can sometimes give the utility an accurate measure of average line temperature and sag, but they may be needed on every dead-end section of line, are expensive, and can be inaccurate if line sections are not straight or don't have insulators that can swing freely enough. These systems can only give average sag, tension, and temperatures and do not tell precisely where the hot and cold spots are nor where ampacity limitations exist without other calculations and data. The data can therefore contain large errors. Point-line temperature measurement systems suffer from similar drawbacks, not always knowing where the actual hotspot is without significant increases in the number of measurement points.

Weather-based systems are typically less expensive than temperature and tension-sag systems, which require the installation and monitoring of additional sensors.[6,7]

This paper focuses on using weather and environmental measurements to dynamically rate transmission lines. A system developed by Idaho National Laboratory (INL) and Idaho Power uses larger volumes of weather measurement equipment installed along the transmission lines to be dynamically rated. The weather measurement equipment collects data such as wind speed, wind direction, ambient air temperature, and solar irradiance levels at predetermined locations, and is used to model and calculate a more complete and accurate picture of the weather conditions and temperatures along the full length of transmission lines of interest. Weather parameters are obtained from local weather stations, mounted on power line poles.

WindSim, a Computational Fluid Dynamics program, is a popular wind modeling tool typically used to simulate the wind conditions for siting a wind farm. In this application it is being used to estimate wind conditions on a transmission line between weather stations using information from the stations along the line. A unique aspect of this project is using WindSim to simulate wind conditions over a much larger geographic area than is typically employed. Inputs to WindSim include the temporal wind information obtained from 17 weather stations located within the region of interest and the terrain. WindSim is then used to estimate the wind velocity along the length of the line and in particular at the middle of the sag. The middle of the sag, being the lowest in elevation, is often considered the worst case position because the wind speed is generally at a minimum at lower elevations. By including information about the variation and surface roughness of the terrain, the WindSim program is better able to estimate the wind velocity, taking into account the topography of the land.

Additional software programs take the estimated wind speed and the load on the line, and determine the cooling effect. From this process the rating of the line can be adjusted to accommodate greater loads when the wind is sufficiently blowing.

This new methodology has important implications for future policy/regulation and utility use of dynamic line rating. The DLR concept has been around for a long time, but has not gained wide use and acceptance by utilities because of a common understanding that implementation can be challenging and costly, and still may not always capture the actual line section that is limiting the whole transmission line at any one time.

3. OBTAINING ENVIRONMENTAL WEATHER PARAMETERS

The main goal is to determine the temperatures of the conductor along all sections of the line. Once the conductor temperature is determined, the line rating can be adjusted to allow more energy to flow while simultaneously maintaining the temperature in its proper range. Line sag increases as the temperature increases. The physical limits of line sag generally determine the upper bound of the line core temperature. The utility power company generally measures transmission line currents. Environmental parameters such as ambient temperature, sun radiation, wind speed and direction, are used, along with line current, to calculate the line core temperature for given environmental and line current conditions. The IEEE Standard 738-2006[10] lists the equations commonly used to calculate the current-temperature relationship of bare overhead conductors.

In this case, 17 weather stations are used to measure the environmental information. It is important to have this information along the entire length of the line. The segment that results in the highest core temperature will determine the rating of the entire line.

The WindSim program is used to model the wind patterns along the full length of the line. The wind simulator estimates the wind speed and direction in the defined modeling region containing the 17 physical weather stations.

Wind speed and direction are the most significant environmental factors in determining the core temperature[9] of overhead conductors. Maximum convective cooling occurs when the wind direction is perpendicular to the line. Wind blowing parallel to the conductor results in a 60%[8] lower convective heat loss than wind that is perpendicular to the line.

This project looks at the cooling effect of the wind on several transmission lines, over varying terrain, for about 30 miles of line. This area was chosen because of the varied terrain, the number of available weather stations, and to better compare test data to simulated data.

Significant wind power generation is also available in this region. It is desired to show that when the wind blows, which results in higher wind power generation, the lines can be dynamically rated higher because of the concurrent cooling that takes place when the power from wind is being generated.

4. WIND SPEED MODELING USING WINDSIM

The WindSim modeling program is based on classical 3-D Reynolds-Averaged Navier-Stokes equations. Solving the nonlinear transport equations for mass, momentum, and energy makes WindSim a suitable tool for simulations in a complex terrain.[9] Typically, the mass and momentum equations are solved to predict the wind velocity in the region of interest; the energy equation is applied for heat transfer. This study focuses on the wind velocity.

WindSim is a popular tool for evaluating the potential energy capacity of wind farms. The modeling algorithm uses the land topography to simulate changes in wind velocity based on geographic effects. It is a natural tool to simulate wind velocity for power line cooling. As the terrain varies, significant variations of wind speeds occur.

Assessments of wind resources are accomplished with both experimental and numerical means. Wind modeling for this project involves a larger area of ground than what is done for a typical wind farm. Temporal data from a limited number of weather stations are used in the numerical model to assess the wind resources for a larger area. The numerical model calculates the terrain-induced changes to the wind field.

Local wind fields are highly influenced by local topography. The input basis for WindSim consists of a digital terrain model with a length scale sufficient to describe the geography within the applied mesh, according to the phenomenon under consideration. Additional refined modeling can then be completed using WindSim with a variety of length scales ranging from detailed, micrositing models up to larger mesoscale wind models. WindSim models the region of interest by placing a body-fitted-coordinates mesh over the topography. The body-fitted mesh defines the land features such as hills, valleys, ridges, and other large topographical features that affect wind patterns. A variable-spaced mesh is used in the z-direction to provide more refinement near the ground and a larger spacing out towards the free-stream velocities. Grid refinement near the surface more accurately tracks velocities within the boundary layer, especially wind patterns that are affected by geographic effects.

In addition to the topographical land forms modeled with the digital terrain inputs, surface roughness is included in the model to account for terrain effects that are smaller than the grid. These effects can include topographical effects as well as trees, shrubs, and buildings, which also affect wind patterns. Terrain roughness has a particular influence on wind speed at the zone near the ground.

To provide a level of calibration to the model, WindSim requires meteorological data from at least one point within the modeled area. Additional points provide more information to fine tune the model within the defined grid. Using these inputs, wind resources for a broad area can be calculated, potential energy production from any number of wind turbines can be obtained, and the area with infrastructure can be visualized in the 3-D interactive visualization module.

WindSim meteorological data for this project uses 17 physical weather stations installed at various locations along the transmission line structures. WindSim is then used to simulate the wind speed and direction at various points of interest along the power line. A mobile, trailer-based, weather station (mobile MET-testpoint) is used to gather data at various locations to validate the simulated results generated by WindSim. Figure 1 shows the location of 15 of the weather stations and the transmission lines.

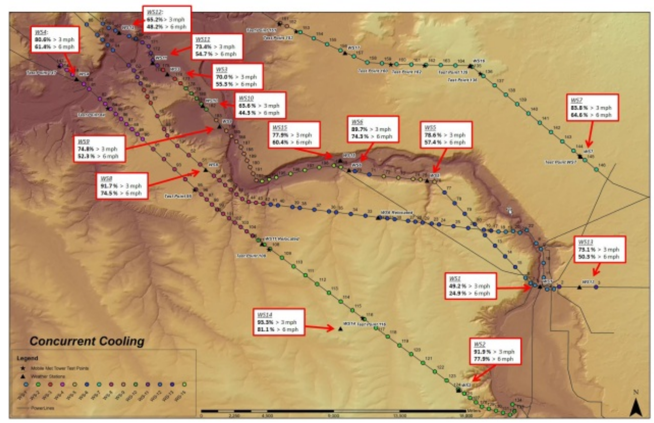

Figure 1. Weather station average wind speed.

5. WIND SPEED SIMULATION

The area currently studied is located on the Snake River Plain in southern Idaho. It was chosen because of the variety of land topography and ease of access to locate weather stations for operation and validation. Figure 2 shows the project area.

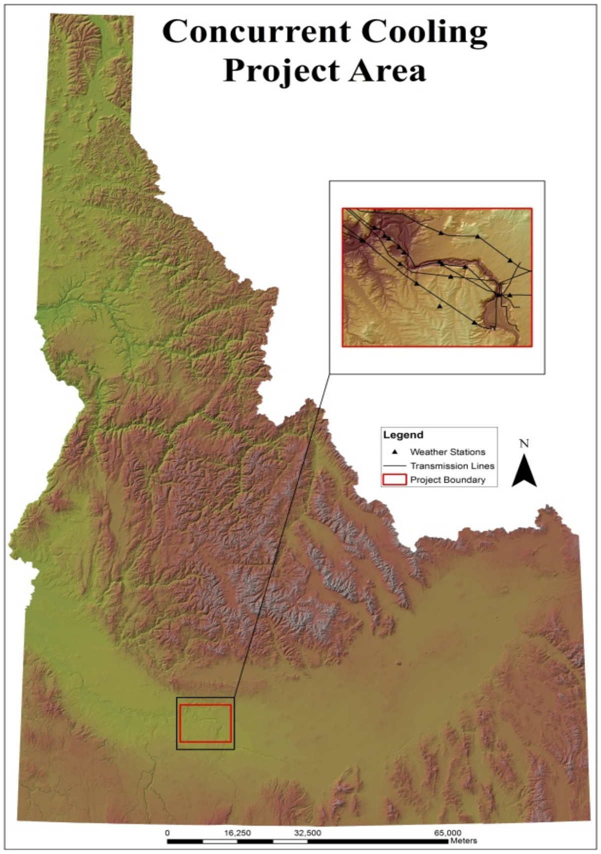

Figure 2. Location of project area.

The weather stations are mounted on the power line structure at a height of 10 meters (represented by triangles in Figure 3). The data at these points are inputs into the wind speed simulator, WindSim. The output of the simulator is indicated by the circles, in Figure 3. Test points are used to validate the model by using a mobile station and locating it near a WindSim output point for comparison.

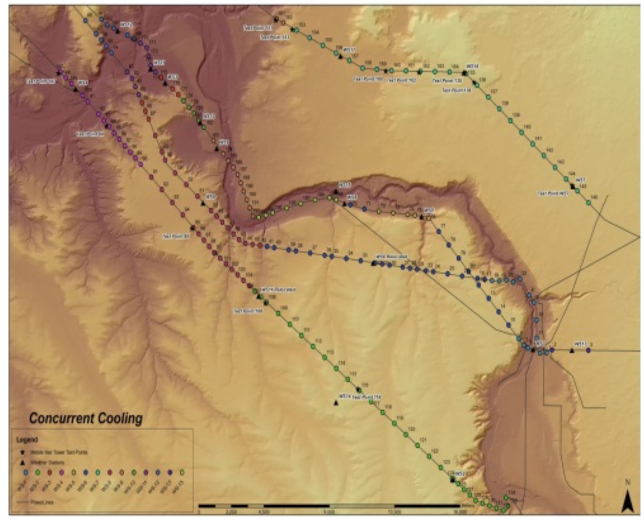

Figure 3. Power line corridor test points.

Modeled wind speeds were directly compared to measured wind speeds collected from the mobile met tower. Figure 4 displays the modeled data adjusted by ±20% and the mobile met tower data for Model Point 95 and Test Point 95. Although the wind speeds measured by the mobile met tower at times exceed the error bounds generated from the model, measured results during the majority of time remain within the error bounds. Wind speeds outside of the ±20% band typically only last for a few 3-minute time samples. In general, modeled results appear to be more accurate at higher wind speeds than they are at lower speeds. Accurately modeling the wind is more difficult at lower wind speeds because of greater variability in the wind flow.

Figure 5 shows a visual of the body fitted coordinates mesh and digital terrain models. These inputs to WindSim provide information about land topography.

Terrain

2D Field 3D Model Extension 3D
◄ ► 3D Model: Grid (xy)

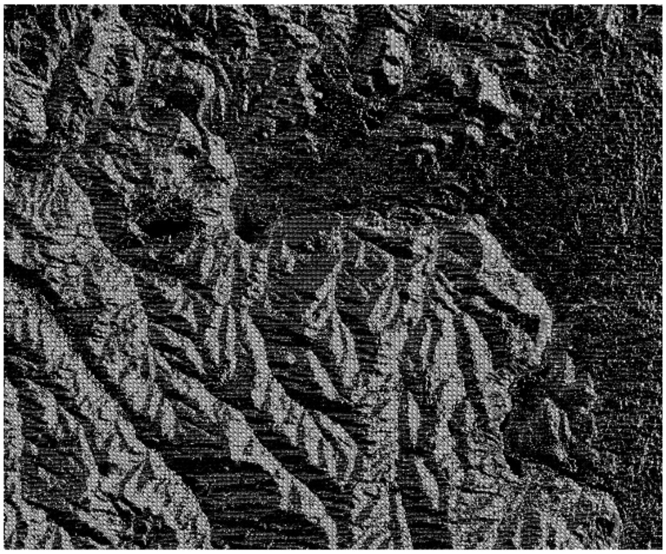

Fig 1. Digital terrain model - Grid (xy).

Body fitted co-ordinates (BFC) are used in grid generation. The above plot displays the resolution at ground level.

	x	y	z	total
Grid spacing, min - max (m)	44.2 - 44.3	44.1 - 44.2	Variable	-
Number of cells	991	807	60	*******

Table 1 Grid data

48,000,000 cells

Terrain

2D Field 3D Model Extension 3D

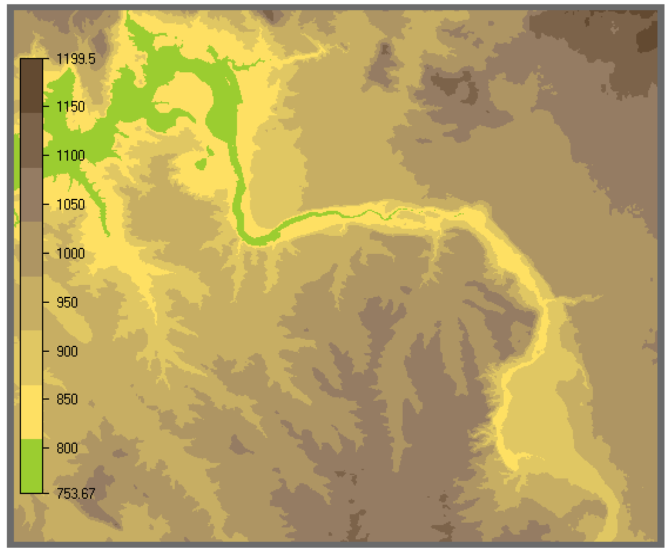

Fig 1. Digital terrain model - Extension.

The digital terrain model, marked as a box, is extracted from grid.gws.

x-min	x-max	y-min	y-max	x-extent	y-extent	resolution
390219.1	434049.1	180171.0	215841.0	43830.0	35670.0	Variable

Table 1. Digital terrain model, .

x-min	x-max	y-min	y-max	x-extent	y-extent	resolution
390219.0	434049.0	180171.0	215841.0	43830.0	35670.0	30.0

Table 2. Data in grid.gws

Figure 4. Assembling the digital terrain model.

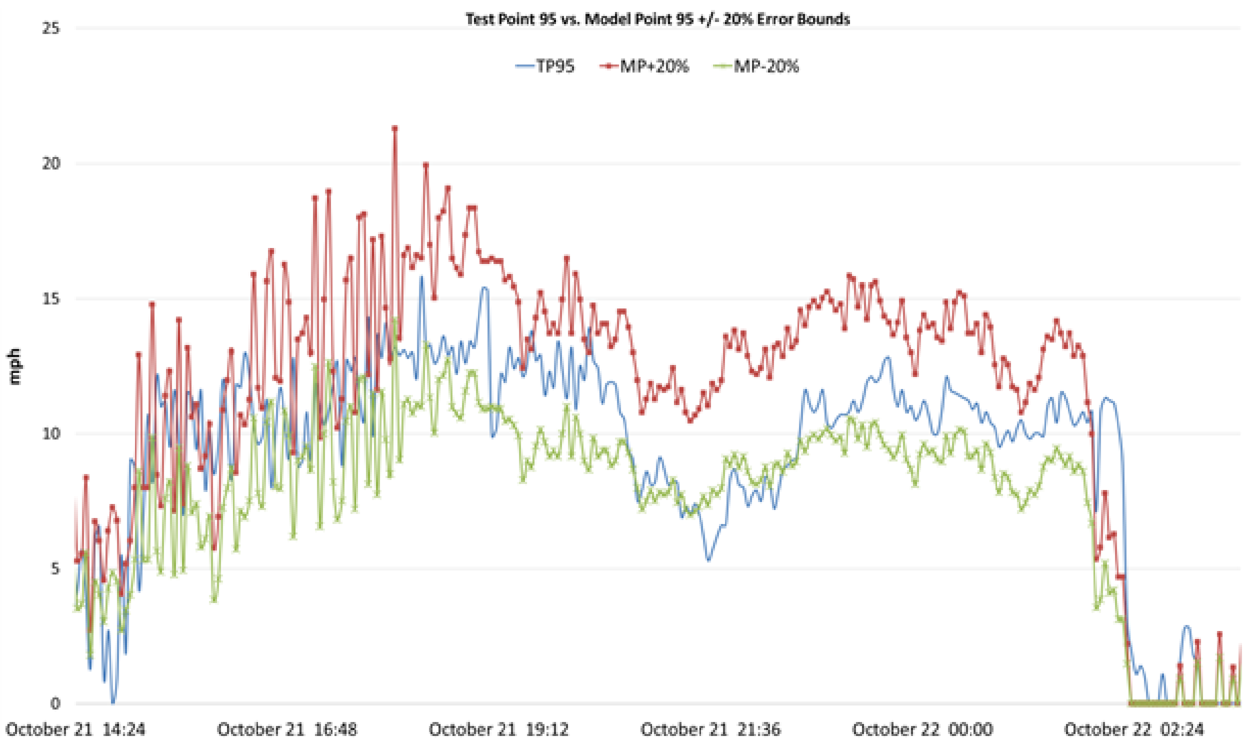

Figure 5. Comparison of measured and simulated wind speeds at Model Point 95.

6. RESULTS AND ANALYSIS

The WindSim modeling process is too computationally intensive to be done in real time. Data is collected from the weather stations every 3 minutes. The collected data is an average of 2-second readings of the parameter over that 3-minute interval. Simulations are performed from time to time and results are loaded into a database. The database forms the basis of a lookup table technique. The real-time data from weather stations is combined with the look-up table information from WindSim to provide the wind speed along the power line. The cooling effect along the line will vary from segment to segment, so it is necessary to determine which segment is receiving the lowest wind speed, and that one is used to determine how to rate the whole line.

It is anticipated that line ratings will be determined for 15-minute intervals.

Once wind speed and other environmental parameters are determined, calculations can proceed to determine the conductor temperature.

Equations used to determine the conductor temperature as a function of current and environmental condition have been used for some time, and are documented in the IEEE Standard 738-2006.[10]

A computing device/system now performs the following calculations:

The heat balance equation is used to calculate the steady-state current carrying capacity of a conductor.

$$q_c + q_r = q_s + I^2R(T_c) \qquad \text{Eq. 1}$$

where:

q_c is the heat removed by convection(air movement)

q_r is the heat removed by radiation to surrounding air

q_s is the heat gained from solar radiation from the sun

$I^2R(T_c)$ is the heat generated by the electron current flow in the conductor

T_c is core temperature of the conductor.

Solving Eq. 1 for the current I, yields

$$I = \sqrt{\frac{q_c+q_r-q_s}{R(T_c)}} \qquad \text{Eq. 2}$$

to determine q_r , q_c, and q_s as

$$q_r = 0.0178D \in \left[\left(\frac{T_c+273}{100}\right)^4 - \left(\frac{T_a+273}{100}\right)^4\right] \qquad \text{Eq. 3}$$

$$q_s = \alpha Q_{se}\sin(\theta)A'. \qquad \text{Eq. 4}$$

The convection heat loss has two equations: the value q_{c1} for low air speed(<3 mph) and q_{c2} for higher air speed:

$$q_{c1} = \left\{1.01 + 0.0372\left(\frac{DV_w p_f}{\mu_f}\right)^{0.52}\right\} k_f K_{angle}(T_c - T_a) \qquad \text{Eq. 5}$$

$$q_{c2} = \left\{0.0119\left(\frac{DV_w p_f}{\mu_f}\right)^{06}\right\} k_f K_{angle}(T_c - T_a) \qquad \text{Eq. 6}$$

The parameters p_f(air density), μ_f(dynamic viscosity), k_f(thermal conductivity), must be calculated for the current ambient temperature. This is done for a specific conductor type (ACSR-715.5) and using data from WS7, which shows that, under varying weather conditions, the line current carrying rating can be increased from 35 to 177%. These calculations need to be performed for each line segment. The least capable line segment determines the capability of the complete line.

Table 1 shows the results of line ampacity calculations at varying wind speeds and directions.

Table 1. Computed possible dynamic line ratings.

Conductor	Respective Weather Station		Line Point	Wind Speed (MPH)	Wind Speed (ft/sec)	Wind Angle	Line Azimuth	Static Summer Rating			Dynamic Winter Rating 5 deg C				Dynamic Summer Rating 40 deg C			
	Baseline							Line Voltage (kV)	MVA	Amps	Line Voltage (kV)	MVA	Amps	Percent Change	Line Voltage (kV)	MVA	Amps	Percent Change
								230.0	433.4	1088.0	230.0	433.4	1088.0	0%	230.0	433.4	1088.0	0%
ACSR - 715.5	WS7	Ave High	161	9.48	13.94	30	90				230.0	1202.3	3018.0	177%	230.0	846.9	2126.0	95%
		Ave High	161	9.48	13.94	15	90				230.0	1069.2	2684.0	147%	230.0	747.3	1876.0	72%
		Ave High	161	9.48	13.94	0	90				230.0	888.4	2230.0	105%	230.0	609.5	1530.0	41%
		Ave Low	160	8.306	12.21	30	90				230.0	1157.7	2906.0	167%	230.0	813.5	2042.0	88%
		Ave Low	160	8.306	12.21	15	90				230.0	1030.2	2586.0	138%	230.0	717.9	1802.0	66%
		Ave Low	160	8.306	12.21	0	90				230.0	857.3	2152.0	98%	230.0	584.8	1468.0	35%

7. CONCLUSIONS

Several methods can be used to obtain the necessary information to dynamically rate an overhead power line. This paper shows some results of using weather stations distributed along a transmission line coupled with wind simulation software to determine the cooling effect of wind upon an overhead power transmission line.

The wind simulation approach allows one to estimate the influence of wind along a large distance with a relatively small number of wind measuring devices.

The results from using this information and applying the cooling effect of the wind demonstrate that the current carrying capacity of the power lines does increase as the wind blows or as other measured environmental conditions improve over those used to establish static line ratings. The initial test system implemented in the sample area for this project shows 10 to 40% improved line capacities for a majority of the time, with improvements over 40% at certain times of higher winds across the whole area.

The major aspect of this project and its approach is dependent on the ability to obtain higher resolution wind data (much more resolution than previous approaches), which is of adequate quality and can be depended upon to yield reliable conclusions. Additional work could be pursued to further test and validate for improved accuracies and to determine the sensitivities of the system and its robustness in the event of a system failure or errant data.

This new methodology has important implications for future policy/regulation and utility use of dynamic line rating. The DLR concept has been around for a long time, but has not gained wide use and acceptance by utilities. This appears mainly because of a common understanding that implementation can be challenging and costly, and still may not have the resolution and accuracy to always capture the actual line section that is limiting the whole transmission line at a particular time.

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