PROBABILITY BASED ALLOWABLE CURRENT RATINGS FOR BPA'S TRANSMISSION LINES

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1.0 Abstract
Allowable current ratings for BPA's transmission lines are presently based on conservative deterministic criteria. This conservative criteria has served BPA well for many years with minimal cost penalty as most lines have historically been stability limited. Beginning in the mid-70's, a number of BPA's lines have shifted from stability limited to thermally limited, suggesting the conservative assumptions in the present allowable current rating model may be associated with significant cost penalties. A new method, based on probabilistic techniques, is described which diminishes the conservative assumptions in the present deterministic method promising substantial cost savings. General probabilistic equations are developed and the overall technique's philosophy discussed. The probabilistic method revolves around statistical ambient weather models which are reported. Research work has been performed to characterize weather regions in BPA's service area assembling limited statistical weather models for each region. Planned future work is outlined including the development and deployment of a data acquisition system capable of collecting ambient weather data in support of probabilistic line ratings.

2.0 Introduction and Background
Allowable current ratings for BPA's transmission lines are intended to ensure safe line operation while promoting maximum power transfer. Ground clearance requirements are based on the National Electrical Safety Code (NESC or Code) and provide adequate clearance to allow an anticipated activity to coexist safely with an overhead line. BPA's present current rating model is deterministic and hence conservative as it is based on a set of extremely rare ambient weather conditions.

2.1 Clearance Over Underlying Activities
Minimum Code clearances for overhead lines are built up from an assumed activity plus an insulating air gap. These minimum clearances are sufficient to allow the coexistence of the overhead line and the protected activity. Meeting and maintaining Code requirements are obviously ethical, prudent, responsible, and reasonable; and hence are considered a paramount operating constraint at BPA. BPA considers minimum Code clearances the "floor" which BPA will not sag below, and to that end, BPA provides additional clearance buffers to Code values to obtain a high assurance level (98%) NESC clearances are met in the field. Discussion of BPA clearance buffers and specific Code requirements is beyond the scope of this paper.

2.2 Conductor Maximum Operating Temperature
Current passing through a conductor generates resistive energy losses, which translate into thermal energy gain raising the conductors overall temperature. Since metal expands with temperature, the length of conductor between supporting structures also increases. This increase in conductor length translates into greater conductor sag reducing ground clearance. A lines Maximum Operating Temperature (MOT) is the highest temperature at which a conductor can operate and still maintain NESC minimum clearance requirements for safe line operation. Other constraints limiting allowable current ratings are general and localized conductor loss of strength through annealing, and inadequate compression fittings. Conductor annealing and compression fittings are beyond the scope of this paper.

Almost without exception at BPA, MOT is between 50°C and 100°C and is the constraint which usually limits allowable current ratings. All BPA lines designed prior to 1979 are based on a maximum conductor temperature of 50°C which is a direct outgrowth of NESC requirements. The upper limit of 100°C is based on operating economics and the onset of conductor annealing. BPA allowable current ratings are identified by line, which if exceeded, result in an unacceptable risk of that line's operating temperature exceeding its MOT resulting in NESC impaired field clearances.

3.0 Conductor Temperature and Current Flow; General Computational Scheme
For overhead lines at BPA, the conductor is a bare wire suspended between two supporting structures exposed to surrounding ambient conditions. Electrical current flowing within a conductor (Figure I) experiences resistance and must expend energy over coming that resistance to complete its path from energy source to load. This lost energy associated with current flow manifests itself as heat gain within the conductor ($\Phi_{\text{Resistive}}$). The conductor is also assumed exposed to the sun with an associated solar heat gain ($\Phi_{\text{Solar}}$). Heat loss is primarily driven by the temperature difference between the conductor and its surrounding ambient, being significantly enhanced by the cooling effects of wind in the convection term ($\Phi_{\text{Convection}}$ and $\Phi_{\text{Radiation}}$).

Figure I: Steady State Conductor Heat Flow

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3.1 Steady-State Heat Balance Equation

Allowable current ratings for BPA transmission lines are computed under assumed steady state conditions. Steady state is the special case where heat flow out of the conductor is equal to its internal heat generation and heat flow into the conductor. The four bulk parameters comprising the heat balance equation and their associated relationships to conductor material and surface properties and ambient weather conditions are summarized in the following equations (the reader is referred to IEEE Standard 738-1988 for a more rigorous treatment of the following relationships).

\[ \Phi_{\text{con}} + \Phi_{\text{rad}} = \Phi_{\text{esat}} + \Phi_{\text{sol}} \]  

(1)

where,

\[ \Phi_{\text{esat}} = I^2 R_{\text{ac}} \]  

(2)

\[ \Phi_{\text{rad}} = \alpha D_0 \sum \frac{\sin(\theta)}{12} \]  

(3)

\[ \Phi_{\text{con}} = \left[ 1.01 + 0.371 R_{\text{ej}}^{0.90} \right] \left( T_c - T_a \right) \]  

(4)

or,

\[ \Phi_{\text{con}} = 0.1695 R_{\text{ej}}^{0.6} \left( T_c - T_a \right) \]  

(5)

and,

\[ \Phi_{\text{rad}} = 0.138 \times D_0 \left\{ \frac{K_B}{100} - \frac{K_A}{100} \right\} \]  

(6)

\[ R_{\text{ej}} = 12 D_0 P \frac{V}{\mu} \]  

(7)

3.2 Conductor Temperature and Current Flow

The relationship between conductor temperature and current flow is found by rewriting equation 1 and substituting equation 2 for the resistive heat gain term (Equation 8).

\[ I = \left[ \left( \Phi_{\text{con}} - \Phi_{\text{rad}} - \Phi_{\text{sol}} \right) / R_{\text{ac}} \right]^{0.6} \]  

(8)

The relationship is straightforward with the physics and material properties adequately understood. Additionally, the analytical relationships have been demonstrated accurate by numerous laboratory simulations. Therefore, for a specific situation or site analysis under steady state conditions; the current flowing in a conductor can be determined from the conductor's temperature (or vice versa) if ambient temperature, solar radiation, and effective wind speed can be accurately quantified. In essence, the determination of allowable current ratings for a transmission line is not so much the calculation of current levels, but more the direct result of the ambient weather model used to characterize the conductors surrounding environment. The determination and characterization of an ambient weather model, and its impact on conductor temperature and/or ground clearance, is the challenge of any allowable current rating scheme and is the remaining focus of this paper.

4.0 Deterministic Current Ratings

Before describing the probability based allowable current rating scheme, it is instructional to contrast the new technique with BPA's present deterministic allowable current rating scheme. As discussed, any allowable current rating scheme for bare overhead supply conductors is essentially a scheme to (1) determine and characterize the ambient weather model and (2) apply that model to the calculation of allowable current levels. The ambient weather model presently used to determine allowable current ratings for conductors at BPA is deterministic and collectively conservative. The model uses an extreme set of ambient conditions and qualitatively judges the conditions to occur so infrequently the resulting rating is deemed safe. Based on past operating experience, the ratings are safe as there have been no reported occurrences of hot conductors sagging into conflicting activity.

4.1 Ambient Temperature

BPA's ambient air temperature model employed for BPA's operators is seasonally and regionally adjusted. Summer ambient air temperatures are assumed 30°C through out BPA's service area. Winter ambient air temperatures are assumed 5°C west of the Cascades and 0°C east of the Cascades (Table I). There is no specific calendar date when the winter and summer models become effective, the winter ratings are intended to be used during winter conditions and the summer ratings are intended for summer conditions.

The ambient air temperature model used for BPA's planners is also seasonally and regionally adjusted in alignment with BPA's Reliability Criteria for System Planning. Summer ambient air temperatures are assumed 30°C through out BPA's service area. Spring ambient air temperatures are assigned a value of 20°C. Winter ambient air temperatures take on various values depending on line location and type of winter storm being used to study system electrical stability (Table I). There are no specific calendar dates when the various season models become effective, the ratings are intended to be used commensurate with the seasonal conditions being studied.

<table>
<thead>
<tr>
<th>Ambient Model</th>
<th>Coast and Puget Sound</th>
<th>West of Cascades</th>
<th>East of Cascades</th>
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</thead>
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<tr>
<td>Planning</td>
<td>30</td>
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<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Spring</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Normal Winter</td>
<td>-5</td>
<td>-5</td>
<td>-15</td>
</tr>
<tr>
<td>Intermediate Winter</td>
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<tr>
<td>Abnormal Winter</td>
<td>-15</td>
<td>-15</td>
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<tbody>
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<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Winter</td>
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<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wind Speed (fps)</th>
<th>Coast and Puget Sound</th>
<th>West of Cascades</th>
<th>East of Cascades</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
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</tr>
</tbody>
</table>

Table I: Parameter Values for Deterministic Current Ratings

4.2 Wind Speed and Direction

Wind speed and direction are presently modeled collectively conservative. Wind speed is set at 2 fps (1.4 mph) for BPA's service area and assumed to impinge perpendicular to the conductor, which maximizes the wind's cooling effects. The model is collectively conservative as the wind speed selected is low enough to more than offset the optimistic assumption of perpendicular yaw angle.

4.3 Allowable Current Ratings

A lines allowable current ratings are those values of current which satisfy the heat balance equation using the appropriate ambient weather model and equating conductor temperature equal to MOT. Thermally and electrically constraining conductor operation at BPA is intended to (1) ensure adequate ground clearance is maintained in the field for safe line operation, (2) control conductor annealing to ensure adequate strength is maintained in the conductor to withstand extreme mechanical loads, and (3) ensure the few marginal conductor fittings presently on BPA's system will not thermally break down and eventually part their conductor.

5.0 Probabilistic Current Ratings

The primary purpose for developing allowable current ratings for...
overhead transmission lines at BPA is to (1) ensure the conduc-
tors maintain adequate field clearance to allow their safe coexis-
tence with assumed under lying activities and (2) ensure the con-
ductors and their fittings retain adequate strength to withstand
and extreme mechanical loads. BPA presently uses a deterministic
rating scheme to assign allowable current ratings to its numerous
lines, and through the use of conservative ambient weather mod-
els, deems the ratings adequate to meet rating goals. Although
the deterministic method has provided safe allowable current rat-
ings; the method can not quantify that level of safety, only that
the resulting ratings are safe.

The deterministic method results in safe current ratings, but it
does not result in a zero probability of sagging below minimum clearances in the field. Probabilities can be driven to very small
values but they cannot be reduced to zero, as there will always be
an ambient condition which will result in conductor temperatures
greater than MOT. Conversely, the deterministic method can also
result in current ratings which are extremely safe and quite pos-
sibly not incrementally justified.

The probability based rating scheme to describe has promise
of being a substantial improvement over the present deterministic
method. The promise of an enhanced method is based on (1) the
conservative basis of the present rating scheme, (2) the ability
to quantify assurance level clearances associated with conductor
temperatures in the field, and (3) an improved understanding and
quantifying of the ambient conditions to which overhead conduc-
tors are exposed. The probabilistic method would upgrade the
ambient weather model in BPA's service area to statistically de-
scribe the coincident occurrence of ambient temperature, wind
speed, wind direction, and other pertinent weather parameters.
With a statistical weather model, probabilities of conductor tem-
perature can be calculated as a function of current flow for any
overhead line. Once identifying an acceptable assurance level to
which clearances shall be maintained in the field (exclusion level),
the allowable current rating for a line becomes that current level
which results in a probability of meeting field requirements at the
prescribed exclusion level.

5.1 General Probabilistic Model

The primary goal for maintaining minimum NESC clearances in the
field and developing allowable current ratings for overhead lines is
to protect limited underlying activities from damage due to voltage
flashover. The clearance relationship between NESC minimum
clearances and underlying activities can be modeled as two
clearance zones; a zone adequate in height to allow the activity
and an insulating zone protecting it from flashover. The conduc-
tors and its supporting structures are placed in the field to main-
tain those minimum NESC clearances at MOT. The flashover rela-
tionship, therefore, between the conductor and its underlying activity
can be viewed as dependent upon (1) the underlying activity be-
ing present, (2) the insulating air gap withstand voltage, (3) the
installed clearance meeting NESC minimum requirements, and (4)
conductor operating temperature not exceeding MOT.

Based on the above, the probability of experiencing a flashover,
or flashover event (E\text{f}), is the probability of the conflicting activity
being present (A\text{p}) times the probability the energized conductor
will flash the gap (F\text{p}) times the probability actual clearance will be
at or below required clearance (C\text{p}) times the probability the con-
ductors temperature exceeds MOT (T\text{p}). Assuming the distribu-
tions are normal and independent, the probability of flashover to
an underlying activity is;

\[ E_f = p(\text{flashover to conflicting activity}) \]  
\[ \text{or,} \quad E_f = A_p C_p T_p F_p \] (9)

The probability term for conductor temperature exceeding MOT, is
itself dependent on the probability of line current exceeding al-
lowable rated current (I\text{p}) times the probability of experiencing
ambient weather conditions capable of producing conductor tem-
peratures in excess of MOT at rated current (W\text{p}). These distri-
butions are also assumed normal and independent or;

\[ T_p = I_p W_p \]

(11)

Note the equations do not include a cross correlation term as they
were assumed normal and independent. The equations also as-
sume the conductors thermal inertia is zero, hence conductor
temperature is modeled to respond instantaneously to changes in
current loading and/or weather conditions. Both of these as-
sumptions are simplifying assumptions and tend to offset one an-
other. The conductor temperature cross correlation term tends to
increase computed probabilities and the thermal inertia of the
conductor tends to dampen that value. The generalized probabil-
ity function of a flashover event is then;

\[ E_f = A_p F_p I_p C_p W_p \] (12)

Equation 12 identifies the major terms for computing the probability
of a flashover event as being related to the activity, the insu-
lating air gap, the magnitude of current flow, the installed clear-
ance in the span, and the ambient weather conditions.

5.2 Conflicting Activity Probability Model

All clearances at BPA include a protected zone of adequate height
to accommodate an underlying activity as specified by the
NESC (i.e., 14 foot trucks). The conflicting activity model is the
probability the activity is present in sufficient height to completely
fill the protected zone.

\[ A_p = p(\text{activity present}) \] (13)

Although the protected zone is usually not occupied at all times,
this analysis assumes the conflicting activity is always present
(A\text{p}=1.0). This assumption is most expedient since (1) a depend-
able statistical model describing the expected frequency of a
conflicting activity is not available, (2) the assumption is conser-
ervative, and (3) it is in alignment with the present rating method.

5.3 Flashover Probability Model

Clearances specified in the NESC include an air gap of sufficient
magnitude to insulate the activity from flashover at a high assur-
ance level. The flashover probability model is the probability of
flash over the air gap at the insulating clearance specified by the
Code.

\[ F_p = p(\text{air gap flashover}) \] (14)

The probability of not flashing across the NESC air gap has an
assurance value greater than three sigma (99.87%). Additionally,
the NESC provides a 24 to 30 inch buffer in Code clearances to
provide a safety margin. This probabilistic model does not sepa-
rate the insulating air gap and buffers but considers their sum
an enhanced insulating zone. Although the probability of
flashover using NESC clearances is very small (less than one in
ten thousand breaker operations), this model assumes flashover
will occur if conductor clearance drops below minimum NESC
clearances (F\text{p}=1.0). This assumption is based on (1) probability
of flashover with decreasing clearance is non-linear, (2) switching
surge values and air quality are not necessarily well defined for all
lines, and (3) provides another level of conservatism consistent
with present rating method.

5.4 Current Flow Probability Model

Since energy is not stored on BPA's electrical system, energy
generation and demand must essentially be in balance at all
times. This balance in energy flow results in a rise and fall of current loading consistent with changing load and generation patterns. Although all lines on BPA’s system have sufficient thermal capacity to operate continuously at rated current, very few lines operate at full capacity 100 percent of the time. The current flow probability model is equal to the probability a line will exceed its rated current, or:

\[ I_p = p(\text{current}/\text{rated current}) \]  

Although most BPA lines seldom carry rated current, this probabilistic model assumes continuous current flow equal to the lines rated current \((I_p=1.0)\). This development further assumes the current flow model and the ambient weather model are independent, which is a convenient simplification. The corresponding cross correlation term has some positive value, but should approach zero as the current flow probability model approaches one. The continuous current flow assumption is used since (1) it tends to uncouple the inter-dependence of current loading and ambient weather, (2) dependable current loading models for any given line are not generally available, and (3) the assumption is conservative and in agreement with the present rating method. With the continuing wide spread use of SCADA on BPA’s system, the current flow probability model could be quantified on selected lines as a future enhancement requiring a cross correlation term to uncouple current flow and ambient weather.

5.5 Clearance Probability Model
Transmission lines at BPA have always been designed with mechanical buffers added to Code clearances, since resultant field clearances are not always in exact agreement with their design values. This long recognized variance in field clearances about a design clearance is the basis for BPA’s present clearance buffers which obtain a 98 percent assurance level Code clearances are met in the field. A discussion of buffer determination is beyond the scope of this paper, but probabilistic quantification of meeting Code clearances in the field is germane. The Clearance Probability Model is the probability clearances will be less than NESC minimum requirements in the field at MOT, or:

\[ C_p = p(\text{field clearance}<\text{NESC requirements}) \]  

For the last ten plus years, BPA has been engaged in an ongoing project to examine all lines on the BPA system against present NESC clearance requirements to determine their present day MOT. The process models a line’s design by digitizing profile maps and modeling conductor tension as a function of temperature. The computer model is compared against present NESC clearance requirements on a span-by-span basis. The detailed clearance analysis is used to determine a line’s MOT such that Code clearances are meet in the field at a 98 percent assurance level. Lines with a detailed clearance analysis allows the Clearance Probability Model to take on a 2 percent value \((C_p=0.02)\), and lines without a detailed clearance analysis would retain their present deterministic ratings.

5.6 Ambient Weather Probability Model
The ambient weather probability model is the probability of experiencing ambient conditions which result in the conductor exceeding its MOT while carrying rated current. For any value of current their is a range of air temperatures with an associated wind speed which results in the conductor experiencing its MOT. In general, for any air temperature \((T_a)\) there is a corresponding effective wind \((V)\) which results in the conductor achieving its MOT while carrying rated current, hence the ambient weather model for Tai is:

\[ W_{p1} = p(V<T) \]  

The upper air temperature

\[ p(V<T) \]  

Ambient Weather Model
The determination of probabilistically based allowable current ratings has moved from the probability of maintaining clearance to a conflicting activity, to maintaining minimum NESC field clearances at MOT. This narrowing of scope for allowable current ratings was accomplished by making the conservative assumptions that (1) the conflicting activity is always present, (2) the insulating air gap will brake down if the energized conductor is present, (3) all NESC safety margins are part of the insulating air gap, and (4) the conductor is continuously carrying rated current. BPA clearance buffers added to Code clearance requirements are structured to ensure NESC clearances are maintained in the field at a 98 percent assurance level \((C_p=0.02)\). Still remaining to complete the rating scheme is the characterization of a probability based model describing ambient weather conditions in support of the Code’s high assurance level of maintaining the insulating air gap. This development further assumes the ambient weather probability at rated current.

\[ F_{\text{ENESC}} = p(\text{Clr}<\text{NESC}) = p(MOT) \sum_{i=1}^{n} p(V<V_i) \sum_{i=1}^{n} p(T<T_i) \]  

5.7 NESC Probability Model and Rating Basis
A number of primary terms for computing the probability of a line flashing over to an underlying activity have been set to their maximum value of 100 percent \((A_p=1.0, F_p=1.0, \text{and } I_p=1.0)\). These simplifying and conservative assumptions essentially reduce the probabilistic model to the probability of experiencing field clearances less than NESC clearances at rated current. The probability of field clearances being less than NESC requirements \((F_{\text{ENESC}})\), is equal to the clearance probability times the ambient weather probability at rated current.

\[ F_{\text{ENESC}} = p(\text{Clr}<\text{NESC}) = p(MOT) \sum_{i=1}^{n} p(V<V_i) \sum_{i=1}^{n} p(T<T_i) \]  

The simplification probability rating model determines allowable current ratings such that NESC clearances are maintained in the field at a prescribed assurance level. Note the probabilistic technique does not infringe on the Code’s safety buffer, nor does it erode the Code’s high assurance level of maintaining the insulating air gap, nor does it take any liberties with the frequency of conflicting activity or cyclic current flow. The probabilistic rating technique limits itself to ambient conditions as they relate to MOT and field clearances as they relate to NESC requirements.

The probability rating method uses the same heat balance equations as the present deterministic method. The probabilistic method determines current ratings based on the conductors MOT and employ the same clearance requirements as the deterministic method. The basic difference between the two rating schemes is the probability method will statistically upgrade the ambient model and probabilistically determine allowable current ratings against an acceptable exclusion level.

6.0 Ambient Weather Model
The air temperatures of interest for the ambient weather probabil-
of probabilistic allowable current ratings (Ambient Weather Model).

The following proposed ambient weather model has numerous limitations and weaknesses, and a significant amount of conservatism is required to offset the uncertainties in its predictions. The weaknesses are recognized and acknowledged; with the observation the present deterministic ambient model also has many weaknesses requiring conservatism to allow its implementation with a high degree of confidence. The ambient weather model as described is not sufficient to actually implement probabilistic allowable current ratings, but is a "first cut" at a model using the limited data presently available. With enough quality data, the probabilistic rating scheme will eventually characterize the predictor models with sufficient accuracy to allow implementation with an associated significant reduction in conservatism and associated costs. The first cut being described in this paper, even with its conservatism, could partially accomplish that promise if implemented. The deterministic method could never hold such potential as it does not quantify risk nor weigh the cost of alternatives. There is no weakness in the ambient weather model that additional quality data and/or better predictor models could not overcome.

6.1 Weather Data

Building an ambient weather model capable of supporting probability based allowable current ratings requires regional weather data be gathered, reduced, and interpreted into a format quantifying the probability of experiencing ambient weather conditions which significantly impact current ratings. The amount of available weather data in BPA's service area is extensive with temperature data being available at about 450 locations and wind data from about 300 locations in the Pacific Northwest. Most of the above data is either National Weather Service data or Federal Aviation Administration data with BPA contributing data at about 42 sites. Much of the data was not in a format useable to this study (collected daily or weekly) reducing the number of sites to 181 for temperature data and 317 for wind data. The temperature data was further limited as only temperature means for maximum and minimum hourly readings were available and not raw data, which precluded performing statistical analysis to generate standard deviation values to better define measured probability density functions. Wind data was also expressed as the mean of hourly data again precluding statistical analysis to establish standard deviations and directly measured probability density functions. Wind speed data was further exaggerated as many cup anemometers used to collect data have stall speeds of 3 MPH, losing significant amounts of data at low wind speeds. If nothing else is learned from this data review, at least BPA has a better understanding of what data should be collected in support of calculating current ratings.

Although most of the data was in a coarse form as described, a few sites provided data in a format which allowed some statistical manipulation. There were 48 sites with limited data which allowed manipulation of observed wind speeds less than 4 MPH. This limited low wind speed data was used to generate the crude probability density function model used for wind speed. The resulting probability curve is limited, and hence conservative, as it is based on less than ten percent of the wind speed data. Additionally, thirteen BPA sites were used to predict a relation between mean temperature and its associated standard deviation values were not available. It is truly unfortunate to have such a large volume of weather data available, yet only a fraction of the data usable for this effort.

6.2 Weather Regions and Seasons

The number and location of weather regions in BPA's service area in support of probabilistic current ratings has been increased to seven from the present two regions. The regions were reduced from the thirty one climate zones in BPA's service area based on the location of transmission lines, the wind and climate regions, and the availability of weather data. The seven regions are shown on Figure II and seem reasonable considering BPA's service area covers over 300,000 square miles including coastal land, two lowland regions, three mountain ranges, and extensive plateau and range lands.

Seasonally adjusted probabilistic current ratings are based on the traditional four seasons instead of the present winter/summer seasons now used by BPA. The four seasons were selected as they do provide natural boundaries in weather conditions. Selecting the four seasons also seems reasonable as the BPA Reliability Criteria for System Planning and many ongoing planning studies use the seasons of winter, spring, and summer to study system electrical stability.

6.3 Ambient Temperature Model

The maximum and minimum temperature means were generally available at most sites along with hourly temperature data at thirteen BPA sites. As a "first cut" model, the ambient temperature was assumed normally distributed and equal to the average of the mean maximum and minimum temperatures in each region. Furthermore, for the thirteen BPA sites, standard deviation values of temperature were correlated to their mean temperature values to predict standard deviation values for the other sites where such data was not available. The model generates a crude but reasonable probability density function for ambient air temperature using the following associated equations (values of $\delta_0$ are 0.28 winter, 0.25 spring, and 0.16 summer):

$$\tau_T = \int_{-\infty}^{T} \frac{1}{\sigma_T^2} \frac{1}{(2\pi)^{1/2}} e^{-\frac{(T-\mu_T)^2}{2\sigma_T^2}} dT$$

$$\sigma_T = \delta_T \mu_T$$

6.4 Wind Speed Model

The limited amount of low wind speed data (4 MPH or less) was used to build probability predictor models of wind speed. The data generally took the shape of a decaying exponential function suggesting a good fit can be achieved by selecting a Weibull distribution model with shape factor of one (Gamma Type). The model provided a good fit to the data's shape but required further ad-
justment to accurately quantify the observed frequency of wind speeds.

\[ P_v = \frac{k}{(V/\sqrt{2})^k} \left( \frac{V}{V_r/\sqrt{2}} \right)^{-k} \theta \left( \frac{V}{V_r/\sqrt{2}} \right)^k \]  
\[ V_r = 160 P_v^2 + 15.6 P_v \]  

(22)  
(23)

The wind speed model is quite conservative, as the distribution is modeled only on wind data in the 0-4 MPH range. The model was selected as a first attempt to quantify wind speed probabilistically and the conservations were considered appropriate due to the limited amount of quality data at low wind speeds. The shape of the distribution function is similar to a decaying exponential, which weights low wind speeds with a high probability of occurrence and high wind speeds with a low probability of occurrence (Figure IV). The model is further compromised as the mean wind speed used in each weather region is greater than 4 MPH, resulting in probability predictions based on data outside the data range used to generate the overall shape of the distribution function. Hopefully, with better data a more realistic probability density function will emerge also resembling a Weibull distribution, but with a shape factor of two. This distribution would show a positive probability value for zero wind speed, but of a magnitude more appropriate with observed weather data.

![Wind Speed Weibull Probability Density Functions](image)

**Figure IV: Wind Speed Weibull Probability Density Functions**

### 6.5 Concept of Wind Direction

Wind direction for calculating conductor temperature resultant from current flow has always been recognized as a significant contributing parameter. Equally obvious to most designers and researchers is the extreme difficulty in applying it to allowable current ratings in the general case. Perpendicular winds (yaw angle of 90°) maximize convective heat flow and parallel winds (yaw angle of 0°) effectively reduce horizontal convective heat flow to less than 40 percent of perpendicular flow. Neither of the extremes can be logically justified as 90° yaw is very optimistic and 0° yaw is overly conservative. Most utilities, including BPA, make the simplifying assumption of perpendicular flow and rely on low wind speed to retain an overall conservative rating.

Much work and effort has been devoted to characterizing the effects of wind direction on the convective cooling term (i.e., Morgan, Davis, House and Tuttle, etc); but yet no mathematical mechanism has materialized which rigorously allows its inclusion into a general purpose rating model. As suggested by some of Morgan's work, perhaps the concept of prevailing wind direction and conductor yaw angle does not directly apply at low to moderate wind speeds (up to 10 MPH or 14 fps). An alternative wind direction model could include cross wind turbulence into the convective heat transfer term and assume low yaw angle to the conductor. A modified convective heat transfer term (Eq 24), accounting for cross wind turbulence \( \tau \) could be employed. The cross wind turbulence value could assume a low yaw angle (0-20°) and potentially be expressed as a function of wind speed. This is a conservative wind direction model and lends itself nicely to a general rating model. Note the optimistic assumption of perpendicular wind direction has been eliminated (in fact, wind direction in general is eliminated). Data collected at two BPA sites were used to calculate cross wind turbulence as a function of wind speed. At both locations cross wind turbulence was greater than 25° (\( \theta = 0.7 \)) up to a wind speed of about 10 MPH.

\[ \Phi_{\text{Conv}} = \left( 1.01 + 0.371 R_{\text{DAS}}^{0.55} \right) \tau \left( T_C - T_A \right) \]  

(24)

### 6.6 Other Ambient Weather Model Considerations

Although previously mentioned, it is worth reiterating that the bottom line in any current rating scheme is maintaining clearances above conflicting activities at acceptable levels to allow their safe coexistence. Conductors do not respond instantaneously to changes in ambient or line loading parameters, but tend to integrate their effects over an entire span. The conductor is never really at steady-state, but is in a constant state of thermal flux with ever changing ambient and current loading conditions. The conductor integrates all these effects resulting in a gradual (hopefully) change in ground clearance. This integration tends to temper net changes in current flow and ambient conditions and hence ground clearance in response to any point changes in heat balance along the span. It would be instructional to correlate changes in the various rating parameters with ground clearance. Indeed, if ground clearance could be obtained directly, cheaply, and accurately without knowledge of conductor temperature and ambient conditions; the need for this elaborate rating scheme would greatly diminish.

One parameter of significant interest, but with no data found in the expanse of information from the NWS, FAA, or BPA data bases is vertical drafts due to strong solar heating. There is a strong correlation between daytime vertical winds and air temperature due to solar heat. The vertical winds could contribute significantly to convective cooling during times of low wind speed and high ambient air temperature and would closely approximate perpendicular yaw angle. It would be appropriate to include vertical winds in the rating model, especially for low wind speeds and high ambient temperatures.

### Table II: Statistical Parameters for Ambient Weather Model

<table>
<thead>
<tr>
<th>Region</th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \mu_T )</td>
<td>( \sigma_T )</td>
<td>( \mu_V )</td>
</tr>
<tr>
<td>I</td>
<td>42.6</td>
<td>11.9</td>
<td>12.4</td>
</tr>
<tr>
<td>II</td>
<td>40.8</td>
<td>11.4</td>
<td>8.8</td>
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<tr>
<td>III</td>
<td>34.4</td>
<td>9.6</td>
<td>8.2</td>
</tr>
<tr>
<td>IV</td>
<td>35.8</td>
<td>10.0</td>
<td>7.4</td>
</tr>
<tr>
<td>V</td>
<td>31.6</td>
<td>8.8</td>
<td>10.0</td>
</tr>
<tr>
<td>VI</td>
<td>26.7</td>
<td>7.5</td>
<td>9.8</td>
</tr>
<tr>
<td>VII</td>
<td>28.0</td>
<td>7.8</td>
<td>12.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I Coast and Coast Range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II Puget-Willamette Lowland</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III Cascade Mountains</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV Siskiyous-South Cascades</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table II: Statistical Parameters for Ambient Weather Model

### 6.7 DAS for Reliable Statistical Weather Models

A continuing theme throughout this ambient weather model discussion is the lack of quality data specifically tailored to support allowable current ratings. One way to alleviate the dearth of data...
is to collect pertinent concurrent data in support of calculating current ratings and constructing high confidence probabilistic models. Realizing the sooner data collection begins the sooner a significant data base will be available, BPA is designing a prototype data acquisition systems (DAS) to provide quality data to support modeling of the significant parameters discussed in this paper. Depending on what is learned in the prototype phase, it is planned that eventually a number of DAS units will be placed in the field to begin the collection, reduction, and archiving of data in support of allowable current ratings. Hopefully, this data will allow in a realistic probability based determination of allowable current ratings for BPA's overhead transmission lines with the associated potential cost savings.

The prototype is a modified Power Donut coupled with a meteorological weather station and a data logger which performs some rudimentary data reduction. The Power Donut is clamped to the energized conductor and records current flow, conductor surface temperature, air temperature, and ground clearance. The meteorological station records air temperature at three elevations, wind speed in three dimensions (u-v-w), and horizontal wind direction. The data from both units is gathered concurrently by a data logger which attaches a time stamp for future analysis.

The prototype system is installed about three miles from BPA's Ross laboratories and is going through a "shakedown" phase. Once the system demonstrates dependable operation other factors impacting data collection; such as sample rate, extent of on site data reduction, storage capacity, etc., will be investigated and finalized. A limited amount of data will also be collected to obtain a glimpse of the impact of various parameters which presently have little or no data available.

7.0 Conclusions

A method for determining probability based allowable current ratings at BPA which quantifies their level of compliance probabilistically is shown feasible. Along with feasibility, there is a promise for significant reductions in needed conservatism over the present deterministic method with associated cost savings. The probability method described focuses on maintaining NESC clearance requirements in the field and discusses assurance of levels of maintaining same, thus retaining all code safety factors and air gap clearances to ensure flashover will not occur to any assumed underlying activity. Available weather data within BPA's service area is generally insufficient to support statistical weather models with a high degree of confidence. Rudimentary statistical ambient weather models are developed from available weather data and are identified as insufficient to immediately implement probability based allowable current ratings. However, it is concluded that with sufficient quality data, the probabilistic rating scheme will eventually characterize predictor models with sufficient accuracy to support implementation allowing a significant reduction in present day conservatism. To obtain data of sufficient type and quantity to support probabilistic allowable current ratings, a DAS system is under development to gather appropriate data.

8.0 Definition of Terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature standard deviation multiplier</td>
<td>$\delta_T$</td>
<td>Air temperature standard deviation multiplier</td>
</tr>
<tr>
<td>Convective heat flow out of conductor (wts/ft)</td>
<td>$\Phi_{\text{con}}$</td>
<td>Convective heat flow out of conductor (wts/ft)</td>
</tr>
<tr>
<td>Radiation heat flow out of conductor (wts/ft)</td>
<td>$\Phi_{\text{rad}}$</td>
<td>Radiation heat flow out of conductor (wts/ft)</td>
</tr>
<tr>
<td>Resistive heat flow generated in conductor (wts/ft)</td>
<td>$\Phi_{\text{res}}$</td>
<td>Resistive heat flow generated in conductor (wts/ft)</td>
</tr>
<tr>
<td>Solar heat flow into conductor (wts/ft)</td>
<td>$\Phi_{\text{sol}}$</td>
<td>Solar heat flow into conductor (wts/ft)</td>
</tr>
<tr>
<td>Air temperature mean (°C)</td>
<td>$\mu_T$</td>
<td>Air temperature mean (°C)</td>
</tr>
<tr>
<td>Wind velocity mean (fps or MPH)</td>
<td>$\mu_V$</td>
<td>Wind velocity mean (fps or MPH)</td>
</tr>
<tr>
<td>Air temperature standard deviation</td>
<td>$\sigma_T$</td>
<td>Air temperature standard deviation</td>
</tr>
<tr>
<td>Nusselt number crosswind turbulence factor</td>
<td>$\tau$</td>
<td>Nusselt number crosswind turbulence factor</td>
</tr>
<tr>
<td>Conflicting activity probability</td>
<td>$A_p$</td>
<td>Conflicting activity probability</td>
</tr>
<tr>
<td>Ground clearance probability</td>
<td>$C_p$</td>
<td>Ground clearance probability</td>
</tr>
<tr>
<td>Flashover probability</td>
<td>$E_{\text{ESC}}$</td>
<td>Flashover probability</td>
</tr>
<tr>
<td>Air gap probability</td>
<td>$F_p$</td>
<td>Air gap probability</td>
</tr>
<tr>
<td>Current (amps)</td>
<td>$I$</td>
<td>Current (amps)</td>
</tr>
<tr>
<td>Current loading probability</td>
<td>$I_p$</td>
<td>Current loading probability</td>
</tr>
<tr>
<td>Weibull shape factor</td>
<td>$k$</td>
<td>Weibull shape factor</td>
</tr>
<tr>
<td>Weibull wind velocity probability</td>
<td>$P_V$</td>
<td>Weibull wind velocity probability</td>
</tr>
<tr>
<td>Air temperature (°C)</td>
<td>$T_a$</td>
<td>Air temperature (°C)</td>
</tr>
<tr>
<td>MOT probability</td>
<td>$T_p$</td>
<td>MOT probability</td>
</tr>
<tr>
<td>Wind velocity probability</td>
<td>$V_p$</td>
<td>Wind velocity probability</td>
</tr>
<tr>
<td>Ambient weather probability</td>
<td>$W_p$</td>
<td>Ambient weather probability</td>
</tr>
</tbody>
</table>

9.0 References

7. Morgan, VT, "The Real-Time Heat Balance for Overhead Conductors", CSIRO Division of Applied Physics, Australia

10.0 Bibliography

Jerry Reding received BS degrees in Electrical Engineering and Computer Science in 1973 from Oregon State University. After designing transmission lines for Pacific Power and Light he joined Bonneville Power Administration in the summer of 1974. Jerry is presently Chief of the Line Design Section with expertise in areas relating to the design, operation, and maintenance of overhead transmission lines with specialties in conductor design and selection, conductor ratings, compression fittings, insulator mechanics, sag-tension solutions, clearances, and field problems relating to stringing and sagging conductors. Jerry is also a registered professional engineer in the State of Oregon and a senior member of the IEEE.
Discussion

Tapani O. Seppa, The Valley Group, Ridgefield, CT 06877:
The author presents an interesting conceptual plan for probabilistic rating of transmission lines. Although probabilistic ratings cannot be operationally utilized within strict interpretation of the NESC, they can have merit in transmission planning.

The most critical factors in the probability model appear to be:

1. Knowledge of the wind speed and its distribution along the line. Many reports, for example [1] and [2], have shown that wind speed varies significantly spatially. Thus observations at one location do not identify average wind conditions along a long span. The resulting local conductor temperature will vary much more than the average temperature, which determines the clearances. Does the author have any suggestions on how to extend local weather observations spatially?

2. Available low wind speed statistics are not good, as observed by the author. When wind speeds are measured with anemometers with stalling speeds of 3 mph (6 fps), we cannot generate any knowledge of the critical wind speed range of 2-3 fps. Moreover, NOAA sites do not record wind speed averages, they record single hourly observations! On the few sites where true low-speed wind data is collected, the observations are close to Weibull 2 instead of Weibull 1 distribution. This makes an enormous difference. It also appears that if we consider the probability distribution of low wind speeds with averaging times of 15-30 minutes, the probabilities may be even lower than those shown in Weibull 2 distribution [4],[5].

3. Cross correlation factors. Ambient temperature and solar radiation have significant positive correlations with wind speed and turbulence [3], meaning that assumption of statistical independence is overly conservative. Line load may have a positive or negative correlation coefficient with major cooling factors, depending on the line and location [3]. For example, in some areas in Northern California it was found that the lowest diurnal winds occur at early evening, when the line loads are still quite high. At such a location, the assumption of statistical independence is not conservative.

4. Diurnal variation of wind. While many observations support the author's conclusion that the wind speed has a high average directional variation, this is not necessarily true at sunrise and sunset conditions. Conductor temperatures calculated using conductor tension monitoring systems at 90° line angles have indicated that low speed directional winds can occur under such conditions.

Questions can also be raised regarding factors which are not incorporated in the probabilistic model. For example, an accurate probabilistic model should also incorporate dynamic events. Van De Wiel's studies [4] (see Fig. 2) show that temperature increases caused by short circuit currents have a significant statistical impact on the highest sag events. This modifies substantially the clearance risk at extremes. Even his study does not include mechanical events (bounce of conductors) which also coincide with breaker actions! Thus the additional "buffers" in the NESC are there because we do not know everything, and should not be removed unless our clearance models can be made much more sophisticated.

References:

![Figure 1](image1.png)

Fig. 1 Risk of daytime wind speeds of less than 2 ft/sec at three sites in northern California [5]

![Figure 2](image2.png)

Fig. 2 Probability distributions including short circuit temperature rise, according to van Der Wiel [4]

J. L. Reding:
The author thanks Mr. Seppa for his discussion. A note about interpreting requirements of the NESC (Code). The NESC specifies minimum clearances for safety which a utility is required to maintain. The manner in which a utility accomplishes those requirements; whether by a deterministic, probabilistic, or real time scheme, is not specified nor is of concern to the NESC. The Code merely specifies the minimum values a utility must maintain in order to comply.

One of the basic assumptions of the statistical predictors is their general probabilistic application within a weather region. Probabilistically, they should be applicable and appropriate as they are characterizing risk exposure in percentage of time. Therefore, they are not good predictors at any instance of time, but predict overall exposure to weather conditions which could compromise clearances. Plans are to examine this assumption with a number of data collection sites.

Mr. Seppa is correct in noting some low wind speed data is Weibull 2 distributed instead of Weibull 1 as used in the initial wind speed model. We have found that low wind speeds being driven by solar heating are usually Weibull 2 distributed, but other low wind speeds not solar driven (such as night) tend to be Weibull 1 distributed. Low wind speed modeling is still very crude and requires substantially more data and investigation.

The "buffers" in the NESC are not being removed with the probabilistic technique. All buffers and assumptions, both implied and explicite, are retained with the technique. The technique identifies NESC clearances, buffers in tact, as the "floor" which all risks are being evaluated against.

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