

PROSPECTS FOR DYNAMIC TRANSMISSION CIRCUIT RATINGS

K. E. Holbert, G. T. Heydt

Department of Electrical Engineering
Arizona State University
Tempe, Arizona 85287-5706, USA

ABSTRACT

In this paper, the basic concepts of dynamic thermal ratings of overhead transmission conductors are discussed. The sensitivity of these ratings with ambient conditions is evaluated. Innovative concepts in the measurement of overhead sag are given and correlated with dynamic rating of overhead transmission conductors. Dynamic transmission line thermal ratings take on increased importance in the deregulated electric power industry, since transmission capacity is sold as a deregulated commodity. Also, the electric utilities are under pressure to utilize all their transmission resources to the fullest.

1. INTRODUCTION

The U.S. electric power industry is in a transition from a regulated to a deregulated marketplace. Previously, power exchanges between utility service areas were at low levels. Now, competition in a deregulated environment has changed this through an increased need to buy and sell power over long distances. Said power transfers will place greater strain on existing transmission facilities.

The available transmission line capacity (ATC) has always been important as operators attempt to load lines to extract the most out of installed transmission lines. In addition the construction of new transmission facilities is being constrained by environmental issues.

Thermal constraints may cause congestion due to insufficient transfer capacity on a transmission line to implement all energy schedules simultaneously or to serve all generation and demand. As an example, transmission limitations in the American state of California are documented to be crucial to the overall operation of the deregulated system in that part of the world [1].

An important limitation of ATC is the physical, thermal limit of overhead conductors. This issue is discussed in Section 2. Fixed thermal ratings of overhead conductors may not allow system operators to fully utilize existing transmission capabilities. Dynamic ratings, that is ratings which account for ambient conditions, are considered to increase the effective thermal rating. Therefore ATC is concomitantly improved. A key component to dynamic ratings is the inclusion of sensory information. Measurements are integrated with a dynamic line rating algorithm in Section 3. The error analysis of this approach reveals the possibility of significant ampacity prediction inaccuracy. Section 4 addresses this problem by proposing a novel direct measurement technique. This paper is an *overview* intended to complement the literature of dynamic thermal ratings and their application.

2. DYNAMIC TRANSMISSION LINE RATINGS

The term *dynamic ratings* refers to the utilization of real time (or near real time) information to develop accurate ratings of components. In the case of overhead transmission lines, the key elements in the development of a dynamic thermal rating are the conductor composition and construction, its temperature, the ambient temperature, the wind speed, and its direction. The *dynamic thermal rating* of an overhead conductor may be defined as the steady load that produces the maximum conductor operating temperature, computed on an instantaneous basis for actual loading and weather conditions. The *steady-state thermal rating* is the loading that corresponds to maximum allowable conductor temperature under the assumption of thermal equilibrium. The *static thermal rating* may be defined as the current carried by a given transmission line conductor which results in the maximum allowable conductor temperature for a particular set of conservative weather conditions [2].

The power handling capability of an overhead circuit is limited by two main factors: the first is the thermal line rating as described above. The second is a dynamic security rating that relates to the phase angle difference across the line ($V_{\text{send}} - V_{\text{receive}}$). The dynamic security rating is a function of the line admittance: long lines have large angular phase differences for a given line loading, and therefore disturbances cannot be supported as well as in the case of short lines. Figure 1 shows the relationship between line length, thermal ratings and security ratings. For lines of a certain construction, lengths below L are thermally limited, and lengths above L are security limited. It is clear that the full utilization of the cooling of the ambient environment will allow higher circuit loading for short lines. Reference [3] describes an experimental evaluation of dynamic thermal line ratings, and [4] describes EPRI's dynamic thermal circuit rating algorithm.

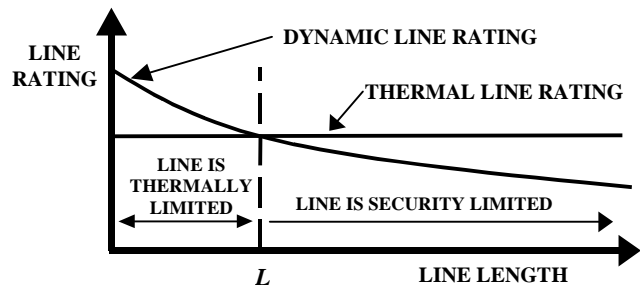


Figure 1. Dynamic and thermal ratings of an overhead transmission line

Present dynamic rating methods use load cells (essentially conductor tension measurement) and instruments mounted on the transmission line for the direct measurement of conductor surface temperature. These methods have the advantage of commercial availability and some experience with their use. Disadvantages relate to their inability to directly give the dynamic line rating and their cost. Differential global positioning system (DGPS) technology seems to offer a potential tool for making more accurate and near real-time measurements of overhead conductor sag. This concept is discussed later.

The value of dynamic line ratings lies mainly in the area of available transmission capacity (ATC) improvement. In a competitive electric power industry, any electric consumer may be able to purchase power from any generating company. This results in two transmission issues: the first is the problem of obtaining circuit capacity for point-to-point transmission, and the second is the development of transmission service from a control area to a load center. In order to preserve system reliability, the $N-1$ type of line contingency study is done. A method known as the maximum steady state load increase (MSSLI) [5] at a specific bus is based on the linearization of system operation near high levels of operation. The MSSLI is a measure of the available increase in system loading without overloading a conductor to its normal thermal rating - even after a single line outage contingency. This index is used to assess the steady state transmission capacity between regions in an interconnected power system. The concept can also be extended to include the dynamic transmission line rating a given conductor temperature and ambient conditions, and the same algorithm used for the MSSLI simulations is applicable.

The MSSLI is defined to be that value of load increase at a given bus for a steady state condition that makes the loading in any line of the system reach rated value when considering the most severe first contingency. The initial conditions of the problem are a given operating condition (base case). The estimation of the MSSLI based on linear system operation is straightforward and based on the use of *distribution factors*, a_{li} , which represent the sensitivity of power flow on line l to a change in generation at bus i ,

$$a_{li} = \frac{\Delta f_l}{\Delta P_i} \quad (1)$$

where l and i are line and bus indices, respectively; ΔP_i is the change in generation at bus i ; and Δf_l is the variation of power flow in line l . Using the definition of the bus impedance matrix, it is possible to estimate the cited distribution factor as [6,7],

$$a_{li} = \frac{1}{z_l} (Z_{bus,ni} - Z_{bus,mi})^* \quad (2)$$

where (*) denotes complex conjugation; i is the generator bus index other than the reference bus; n and m are bus indices corresponding to the line; $z_l = r_l + jx_l$ is the line impedance of line l ; $Z_{bus,ni}$ and $Z_{bus,mi}$ are entries in the Z_{bus} matrix referenced to the system swing bus.

A shift in generation and load at all buses may be required by the sale of power. The shift at the buses is dependent of the way the extra load is going to be served (i.e., either from point-to-point or from control area-to-point). For point-to-point calculations, there

will be load rescheduling only at the two specified buses. For control area-to-point calculations, a generation redispatch is required. Evidently,

$$\hat{f}_l = f_l^o + \sum_i (a_{li} \Delta P_i) \quad (3)$$

where \hat{f}_l is the flow on line l after failure of a generator on bus i and f_l^o is the flow prior to the generator failure. The MSSLI is found iteratively, advancing load level in steps until a system circuit reaches its rating. This method identifies the lines that have reached thermal rating, as well as the corresponding load levels of the entire system. Line outages are accommodated in a similar way, utilizing line outage distribution factors that give the (assumed constant) ratio of additional line loading in a remote line, ΔP_{ij} when a line kl is outaged: the line outage distribution factor is $\Delta P_{ij}/P_{kl}$.

The importance of MSSLI and ATC is that these are indices of how much transmission capacity is available for use by the power companies, how much is available for sale (e.g., the open access same time information system, OASIS [8]), and how much capacity is available to cope with contingencies. These indices are critically dependent on the thermal line ratings of limiting circuits.

3. MEASUREMENTS AND ERROR

The possible measurements for conductor ampacity include wind speed (V_w) and direction (ϕ), ambient temperature (T_a), conductor temperature (T_c), solar radiation, and conductor current (I). The particular measurements utilized depend upon whether, for instance, the Weather Model or the Conductor Temperature Model is employed to predict the thermal line rating. Each measurement not only has an operable range but also an accuracy of measurement. For example, the Power Donut™ has ambient and conductor temperature measurement accuracy of $\pm 2^\circ\text{C}$ over a range of -40°C to 125°C using solid-state thermoelectric sensors [9].

The analytical error propagation technique is applied to quantify the effect measurement errors have on the ampacity uncertainty. Both the systematic error, e , (often referred to as the maximum error) and the random error, σ , can be examined. In most measurement applications, the study of random error is more important since, in all likelihood, the instruments are not all grossly inaccurate. However, if the emphasis is on avoiding catastrophic failure, the maximum error is of greater interest. Catastrophic failure can occur in well-designed systems when a combination of unlikely events simultaneously transpires.

Error propagation methods are well established. We begin with the equations and notation from the Weather Model used by IEEE Standard 738-1993 [2] to determine the ampacity. In general, these relationships follow the form:

$$I = f(V_w, \phi, T_a) \quad (4)$$

The maximum error in I is computed from

$$e_I = dI = \left(\frac{\partial I}{\partial V_w} \right) dV_w + \left(\frac{\partial I}{\partial \phi} \right) d\phi + \left(\frac{\partial I}{\partial T_a} \right) dT_a \quad (5)$$

where dx is the error, e_x , in measurement x . Comparatively, for independent measurements the random error in I is calculated from

$$\sigma_I^2 = \left(\frac{\partial I}{\partial V_w} \right)^2 \sigma_{V_w}^2 + \left(\frac{\partial I}{\partial \phi} \right)^2 \sigma_\phi^2 + \left(\frac{\partial I}{\partial T_a} \right)^2 \sigma_{T_a}^2 \quad (6)$$

where σ_x^2 is the variance in measurement x .

A single representative example of this work is detailed here. Consider the determination of maximum ampacity error when only the wind speed is uncertain, that is, $e_I = (\partial I / \partial V_w) e_{V_w}$. The sensitivity of the ampacity uncertainty due to the wind speed is

$$\frac{\partial I}{\partial V_w} = \frac{\partial I}{\partial q_c} \frac{\partial q_c}{\partial V_w} = \frac{1}{2IR} \frac{\partial q_c}{\partial V_w} \quad (7)$$

which depends on the sensitivity of the convection heat loss (q_c) as a function of wind speed. Since q_c is chosen as the largest of three possible expressions for the convection heat loss, there are three corresponding relations for the sensitivity of q_c with respect to the wind speed, V_w , as shown in Equation (8):

$$\frac{\partial q_c}{\partial V_w} = \begin{cases} \frac{\partial q_{c0}}{\partial V_w} = 0 & V_w < V_1 \\ \frac{\partial q_{c1}}{\partial V_w} = 0.19292 \left(\frac{D \rho_f}{\mu_f} \right)^{0.52} K_{angle} k_f (T_c - T_a) V_w^{-0.48} & V_1 < V_w < V_2 \\ \frac{\partial q_{c2}}{\partial V_w} = \frac{0.6 q_{c2}}{V_w} & V_w > V_2 \end{cases} \quad (8)$$

where q_{c0} is for natural convection; q_{c1} and q_{c2} are for forced convection when the wind speed is low and high, respectively; and V_1 and V_2 are transition boundaries between the convection regimes given by:

$$V_1 = \left(\frac{\mu_f}{D \rho_f} \right) \left[\frac{0.7628 \rho_f^{0.5} D^{0.75} (T_c - T_a)^{0.25}}{K_{angle} k_f} - 2.722 \right]^{1.923} \quad (9)$$

$$V_2 = 6(3600) \left(\frac{\mu_f}{D \rho_f} \right)$$

where V_1 and V_2 are in ft/hr, if the other variables are expressed in the units specified by IEEE Std 738-1993.

Using the above relations, the maximum (e_I) and random (σ_I) ampacity errors are computed for a wind speed error of $e_{V_w} = 1$ ft/s. For ease of reference the other parameter and variable values are taken from the IEEE Std 738-1993 sample calculation for a Drake conductor; specifically, the wind velocity is perpendicular to the conductor ($\phi=90^\circ$), the ambient temperature is $T_a=40^\circ\text{C}$, and the maximum allowable conductor temperature is $T_c=100^\circ\text{C}$. The results of this single study are shown in Figure 2. The largest maximum error occurs at the transition point represented by $V_1=0.54$ ft/s, and the corresponding maximum ampacity error is 278 A. The errorless line rating at V_1 is $I=750$ A, which consequently yields a 37% error. The random ampacity error is almost an order of magnitude smaller than the maximum error.

Additional studies were completed to ascertain the ampacity uncertainty for wind angle and ambient temperature measurement errors. Studies were also performed for simultaneous

measurement errors in all three variables: V_w , ϕ and T_a . The results clearly show that wind speed measurement error is the more important inaccuracy.

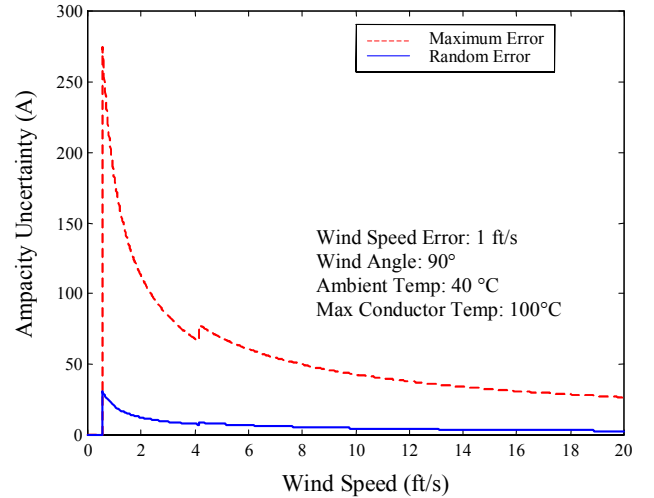


Figure 2. Ampacity uncertainty due to wind speed measurement error only

4. SAG OF OVERHEAD TRANSMISSION CONDUCTORS

As indicated above, the thermal ratings of conductors are important in the calculation of ATC and MSSLI. The two main hardware technologies used in the development of dynamic line ratings are direct measurement of conductor surface temperature and direct measurement of the tension in the conductor. These are

used in combination with real time weather data to develop the conductor physical sag, and also the dynamic line rating. Typically, the methods are accurate to approximately 30 cm for the measurement of sag. There are software-based methods that utilize line loading and weather data to estimate conductor sag, but these methods are believed to be less accurate.

Recently, a potentially more accurate method has been proposed based on the Global Positioning System (GPS). The method uses two GPS measurements with one at a precisely known point: in this way a correction for errors in the remote measurement may be made. The method is known as differential GPS. Figure 3 shows a proposed basic configuration of a DGPS method to measure overhead transmission conductor sag. Normally only one phase of a circuit would be instrumented in a critical span. From the base station, hard-wire is used to bring position data to power system operators. There is a data processing burden in the implementation of the DGPS: this is needed to attenuate noise and enhance accuracy. This burden is calculable in real time using serial on-line processing. The DGPS measurement of overhead conductor sag has produced accuracy in the range of a 17 cm worst error for 70% of the time [10].

The expectation of the foregoing is that new methods of determining overhead transmission line sag can be used to find the MSSLI and hence be used in real time to accurately assess transmission capacity. This translates directly into available transmission capacity for sale -- for example using an OASIS system for open market sale.

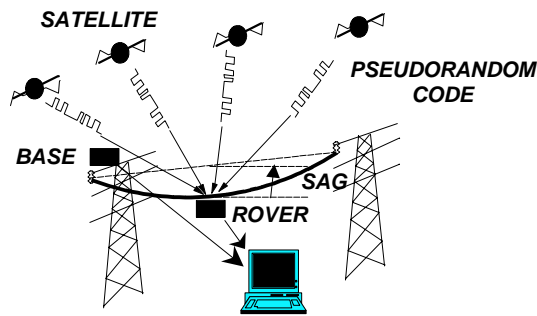


Figure 3. Basic DGPS configuration for conductor sag measurement

5. SUMMARY

The deregulation of the electric power industry is placing increased demands on power transmission system utilization. Increased loading of transmission facilities is an impetus for accurate dynamic thermal overhead electrical conductor ratings. System capacity to transmit power may be quantified by an index known as the maximum steady state load increase (MSSLI). The MSSLI is calculated using linear transmission distribution factors. The accuracy of dynamic thermal ratings is critically dependent on the measurement accuracy of the input variables to the particular prediction model. As an example, wind speed error of 1 ft/s in the weather model can yield a 37% inaccuracy in the predicted line

ampacity in a Drake conductor. As conductor sag is the ultimate desired parameter to quantify the loading of overhead conductors, it is clearly desirable to directly measure sag. An innovative method to measure sag is proposed utilizing differential GPS.

6. ACKNOWLEDGEMENTS

The authors thank the Electric Power Research Institute and the United States Department of Defense for their support of this work. The authors acknowledge the work of Ms. Yuanfang Li and Dr. Chris Mensah-Bonsu.

7. REFERENCES

- [1] H. Singh, "The California electricity market: an assessment of the first year of operations (panel on evolution of electricity market structures)," *IEEE Power Engineering Society Summer Meeting*, Edmonton, Alberta, Canada, 1999, Volume: 2, pp. 753 -755.
- [2] IEEE Std 738-1993, *IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors*, New York, 1993.
- [3] D. A. Douglass, D. C. Lawry, A.-A. Edris, E. C. Bascom, III, "Dynamic thermal ratings realize circuit load limits," *IEEE Computer Applications in Power*, Vol. 13, No. 1, Jan. 2000, pp. 38-44.
- [4] P. M. Callahan, D. A. Douglass, "An experimental evaluation of a thermal line uprating by conductor temperature and weather monitoring," *IEEE Transactions on Power Delivery*, Vol. 3, No. 4, Oct. 1988, pp. 1960-1967.
- [5] U. K. Fernández, C. Mensah-Bonsu, J. S. Wells, G. T. Heydt, "Calculation of the maximum steady state transmission capacity of a system," *Proceedings of the 30th North American Power Symposium*, Cleveland, Ohio, October 19-20, 1998, pp. 300-305.
- [6] G. T. Heydt, *Computer Analysis Methods for Power Systems*, Stars in a Circle Publications, Scottsdale, AZ, USA, 1995.
- [7] R. F. Chu, "On selecting transmission lines for dynamic thermal line rating system implementation," *IEEE Transactions on Power Systems*, Vol. 7, No. 2, May 1992, pp. 612-619.
- [8] J. P. Leotard, M. Ilic, "On the objectives of transmission pricing under open access," *Proceedings of the IEEE Power Engineering Society 1999 Winter Meeting*, pp. 476 - 483.
- [9] N. D. Sadanandan, A. H. Eltom, "Power donut system laboratory test and data analysis," *IEEE Southeastcon Proceedings 1990*, Vol. 2, pp. 675-679.
- [10] C. Mensah-Bonsu, U. Fernández, G. T. Heydt, Y. Hoverson, J. Schilleci, B. Agrawal, "Application of the global positioning system to the measurement of overhead power transmission conductor sag," submitted for publication, *IEEE Transactions on Power Delivery*, 2000.