DYNAMIC THERMAL LINE LOADING MONITOR

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ABSTRACT - Operating a reliable and safe power transmission system is the goal of BPA. In doing so, BPA usually does not attain maximum transmission capacity due to continuous loading thermal limits placed on the transmission system. Thermal limit being the highest temperature at which a line conductor can be operated without violating minimum ground clearance criteria. However, lines do not instantaneously attain their thermal limits. The time it takes a conductor to reach its thermal limit can be used to BPA's advantage (Figure 1). Instead of operating a transmission system to insure that a first contingency does not cause an overload condition, BPA can operate the system at higher current levels provided the conductor's thermal response allows adequate time for manual intervention.

FIGURE 1

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INTRODUCTION

The Dynamic Thermal Line Loading Monitor (DTLLM) monitors the Garrison-Hot Springs and the Hot Springs-Ovando 230-kV lines (Figure 2). Since the method of monitoring both lines is the same, only the DTLLM for Garrison-Hot Springs is discussed in this paper. The DTLLM software calculates the Garrison-Hot Springs 230-kV transmission line thermal capacity* based on real time SCADA data.

FIGURE 2. GARRISON-HOT SPRINGS ONE LINE DIAGRAM

The addition of Colstrip No. 3 generation provides the opportunity for Montana Power Company (MPC) to operate its Interties with the Northwest at maximum capacity. Until 500-kV transmission is extended west of Garrison in the Fall of 1985, the 230-kV system west of Garrison will be operated at levels which will cause

* Thermal Capacity is the amount of current which will cause the line conductor to reach its continuous thermal limit with real time measured ambient conditions. Ambient temperature is monitored in real time while wind speed is assumed 2 fps normal to the conductor.

thermal capacity violations for single contingencies during high ambient temperatures. The DTLLM will make sure initial line loadings are such that at least 20 minutes time for manual intervention will occur before the conductor thermal limit is reached. The DTLLM allows maximum power transfer capability while maintaining safe operation of the system.

The DTLLM software monitors the actual Garrison-Hot Springs line current in amps which is calculated once per minute from SCADA bus voltage, line watts, and line vars:

$$I = \sqrt{(MW^2 + MVAR^2)} / \sqrt{3} V$$

Where,

MW: mega-watts
MVAR: mega-vars
I: conductor current
V: bus voltage

It compares it to the thermal capacity of the line which is calculated once per minute using SCADA ambient temperature and an assumed wind speed of 2 feet/second, and maximum solar heating effects. The DTLLM will provide alarms to the dispatchers when a thermal overload occurs or is expected, and it will indicate how much reduction in line loading is needed to eliminate the overload.

For safe operation of the Garrison-Hot Springs 230-kV line, the conductor temperature must not exceed its thermal limit. If the line current indicates a conductor temperature during a first contingency outage that exceeds its continuous thermal capacity, the DTLLM software estimates the time when the thermal limit will be reached and provides alarm messages for the generation dispatcher.

Many companies have thermal monitoring units located on their lines. BPA has designed thermal line monitoring software which uses SCADA data available from a centralized computer. The advantages to this method are greatly reduced hardware and installation costs.

Computational Procedure to Predict Conductor Thermal Response

The following procedure outlines a technique to predict conductor temperature as a function of time after a step increase in current. Central to the scheme is the assumption of adiabatic heating for each short time interval. The heat gain is assigned to the temperature rise of the conductor above the pre-step steady-state temperature.

The computational procedure begins with the heat balance equation developed by House and Tuttle¹ for computing steady-state conductor temperature:

$$Q_c + Q_r = Q_s + I^2 R \quad (1)$$

Where,

Q_c : Convected heat loss - watts per lineal foot of conductor
 Q_r : Radiated heat loss - watts per lineal foot of conductor
 Q_s : Heat gain from the sun - watts per lineal foot of conductor
I : Conductor current - amps
R : AC resistance - ohms per lineal foot of conductor

The expression equates heat flow out of the conductor (convection and radiation) being equal to heat flow into the conductor (resistive gain and solar gain) under steady-state conditions. At the time of a step increase in current, the above steady-state condition is no longer balanced as the resistive gain has instantaneously increased. The increase in resistive gain can be written as an addition in power (ΔP) to the heat balance equation. The additional power input will raise the conductor temperature over time until the conductor temperature reaches a new value such that the heat balanced equation in (1) is again satisfied. The new steady-state condition will attain a balance between conductor temperature and the new current level such that heat gain in equals heat loss out.

The energy balance equation during transient is

$$P_{in} = P_{out} + \Delta P \quad (2)$$

where,

$$P_{in} = Q_s + I^2 R \quad (3)$$

$$P_{out} = Q_c + Q_r \quad (4)$$

Assuming for a short time interval (Δt) the conductor heats adiabatically consuming the excess energy ΔP . During the conductors temperature increases by ΔT . This increase in conductor temperature from excess energy can be written as:

$$\Delta P \cdot \Delta t = W \cdot S_{pc} \cdot \Delta T \quad (5)$$

or

$$\Delta T = \Delta P \cdot \Delta t / (W \cdot S_{pc}) \quad (6)$$

Where,

W : Conductor bare weight - lbs. per foot.
 S_{pc} : Specific heat of conductor - gram calories per gram degree C

The unit weight of the conductor and the effective specific heat are mechanical properties of a given conductor design.

The entire process can be expanded to the general case by defining the process for each time interval (i). Starting with equation (6):

$$\Delta T(i) = \Delta P(i) \cdot \Delta t(i) / (W \cdot S_{pc}) \quad (7)$$

Substituting (2):

$$\Delta T(i) = [P_{in}(i) - P_{out}(i)] \cdot \Delta t(i) / (W \cdot S_{pc}) \quad (8)$$

Assuming the time intervals are equal and substituting in equation (1):

$$\Delta T(i) = [Q_s + I^2 R(i) - Q_c(i) - Q_r(i)] \cdot \Delta t / (W \cdot S_{pc}) \quad (9)$$

the basic temperature rise equation for time interval (i) is developed. The solar gain term is not subscripted with (i) as it does not vary with conductor temperature so hence not with time. The four subscripted variables (i) vary with conductor temperature, T, and hence with time. At the end of the time interval a new conductor temperature $\Delta T(i+1)$ is computed by adding the temperature increase for the interval to the beginning conductor temperature $T(i)$ or,

$$\Delta T(i+1) = T(i) + \Delta T(i) \quad (10)$$

The remaining text develops the time varying terms as a function of conductor temperature.

Resistance R(i)

Ignoring current flow in the conductor core as being negligible and knowing conductor resistance at a reference temperature R(REF), the conductor resistance as a function of temperature can be written as:

$$R(i) = R(REF) \cdot [1 + (T(i) - T(REF)) \cdot \alpha(REF)] \quad (11)$$

where,

$\alpha(REF)$ - Thermal coefficient of resistance at reference temperature - ohms per degree C
 $T(REF)$ - Reference temperature at which the reference resistance and thermal coefficient of resistance were determined - degrees C

Convective Heat Loss $Q_C(i)$

The convective heat loss term has three forms; one form for natural convection, one form for forced convection at Reynolds numbers (RE) less than 12000, and one for Re number equal to 12000 as used in the House and Tuttle technique. The convective heat loss equations are as follows:

For wind speed equal to zero:

$$Q_C^{(i)} = 0.072 \cdot D^{0.75} (T(i) - T_a)^{1.25} \quad (12)$$

For Reynolds numbers less than 12000:

$$Q_C^{(i)} = [1.01 + 0.371 \cdot (D \cdot P_f \cdot V / \mu_f)^{0.52}] \cdot K_f \cdot (T(i) - T_a) \quad (13)$$

For Reynolds numbers greater than 12000:

$$Q_C^{(i)} = 0.1695 (D \cdot P_f \cdot V / \mu_f)^{0.6} \cdot K_f \cdot (T(i) - T_a) \quad (14)$$

Note terms P_f (air density), μ_f (air viscosity), and K_f (thermal conductivity of air) should be subscripted with an (i) as they vary with conductor film temperature which is a function of conductor temperature as follows:

$$T_f = (T(i) + T_a) / 2 \quad (15)$$

Radiation Heat Loss $Q_r(i)$

Radiation heat loss is a straight forward function of temperature differential, conductor diameter, and conductor surface emissivity (ϵ).

The equation is,

$$Q_r^{(i)} = 0.138 \cdot \epsilon \cdot D \cdot [((T(i) + 273)/100)^4 - ((T_a + 273)/100)^4] \quad (16)$$

Solar Heat Gain Q_s

Although this term has a minor contribution to the energy equation and an insignificant contribution to the shape of the time versus temperature wave form its computation is rather complex. The equation is as follows:

$$Q_s = a \cdot S_s \cdot A \cdot \sin \theta \quad (17)$$

Where,

a - Absorptivity of the conductor surface
 S_s - Solar Radiation of the sun - watts per square foot

A - Projected area of conductor - square feet
 θ - Angle of incidence - degrees

The above term is developed and used as described in reference 1. The various values for the parameters which influence the solar heat gain term can all be programmed on a computer with default values to allow flexibility and usability in the computational procedure. Their values are found in the above reference in tabular form or can be fitted to equations for compact storage in a computer. The software model at BPA uses the maximum Q during the day and uses zero during the night.

USER Interface

A Real Time Operating Dispatch & Scheduling (RODS) computer display for the DTLLM has been developed (Figure 3). The Garrison-Hot Springs 230-kV line is monitored in this display. The line load (MWs) and the ambient temperature are actual measured values received from Hot Springs and Garrison SCADA. The warmest ambient temperature at either Garrison or Hot Springs is selected for the calculation.

The line current (amp), Conductor temperature ($^{\circ}$ C), thermal capacity (amp/MW), time to thermal limit and the required line MW reduction are calculated once per minute. The estimated line load current for an outage of the other 230-kV line is calculated via a post contingency/pre-contingency ratio derived from off-line powerflows studying worst case conditions.

Alarm Conditions

The conditions which initiate an alarm for generation dispatcher are:

1. When line current is greater than thermal capacity.
2. When the line current is greater than 90% of the thermal capacity current (warning alarm).
3. When estimated line current is greater than the thermal capacity and the time to the thermal limit is less than 20 minutes.

Conclusion

The DTLLM model was installed on March 16, 1984, at BPA's Dittmer Control Center on the RODS computer system. It monitors the Garrison-Hot Springs 230-kV line. Nine months of operational experience indicate that the DTLLM is an effective operating tool for the dispatchers. It has been used to increase the transfer capability between Montana and the Pacific Northwest by an average of 50 MW during high ambient temperatures.

DISPLAY DIAGRAMDTLLM - DYNAMIC THERMAL LINE LOADING MONITOR
GARRISON - HOT SPRINGS

	LINE LOAD MW	LINE LOAD AMP	AMBIE TEMP (F/C)	CONDUCTR TEMP (C)	THERMAL CAPAC. AMP/MW	TIME TO THERMAL LIMIT	LINE MW REDUC
GARRISON-HOT SPRINGS ACTUAL LOAD	251	611	44F 6C	32.64	1212 496		0
GARRISON-HOT SPRINGS ESTIMATED LOAD WHEN HOT SPR-OVAND GOES O/S		1021					0

HOT SPRINGS - OVANDO I/S

FIGURE 3

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APPENDIX

List of Symbols

α	= Thermal coefficient of resistance - ohms per degree C.
K_f	= Thermal conductivity of air, watts/ (ft.) ($^{\circ}$ C).
P_f	= Density of air, lb./cu. ft.
μ_f	= Absolute viscosity of air, lb./ (hr.) (ft.)
θ	= Effective angle of incidence of the sun's rays, degrees.
a	= Coefficient of solar absorption.
A'	= Projected area of conductor, square feet per lineal foot.
D	= Conductor diameter, inches.
e	= Coefficient of emissivity.
H_c	= Altitude of sun, degrees.
I	= Conductor current - amperes.
(i)	= The i th interval.
ΔP	= Power difference between steady-state balance - watts per foot.
P_{in}	= Power into conductor system - watts per foot.
P_{out}	= Power out of conductor system - watts per foot.
Q_c	= Convected heat loss-watts per lineal foot of conductor.
Q_r	= Radiated heat loss-watts per lineal foot of conductor
Q_s	= Heat gain from the sun-watts per lineal foot of conductor.
S_s	= Total solar and sky radiated heat, watts/sq. ft.
R	= 60 Hz ac resistance per lineal foot conductor at T ohms/ft.
ΔT	= Temperature rise on conductor for interval Δt .
S_{pc}	= Specific heat of conductor - gram calories per gram degree C.
Δt	= Time interval of computational step.
T	= Conductor temperature - $^{\circ}$ C.
T_a	= Ambient air temperature $^{\circ}$ C.
T_f	= Air film temperature $^{\circ}$ C .
V	= Velocity of air stream, ft./hr.
w	= Conductor unit weight - pound per foot.
Z_c	= Azimuth of sun, degrees.
Z_l	= Azimuth of line, degrees.

I/S = In Service

O/S = Out Of Service

Discussion

Alan McMurtrie (Ontario Hydro, Toronto, Canada): At Ontario Hydro, we have been monitoring thermal line loadings using a similar technique since early 1980. At the moment, it handles 350 circuit sections with a Δt of 30 seconds. A paper on our method appeared in the February 1982 issue of Power Apparatus and Systems, Page 309.

One of our concerns was to find a method that would allow fast calculation of temperature changes, as well as time to limit. This goal was met in both cases, however, the accuracy of the time to limit calculation is of concern to us.

The one thing that the authors haven't pointed out is how they calculate their time to limit. I am very interested in learning what calculation they use.

Manuscript received August 1, 1985.

Fazlollah Vakili, Michael Viles, Jerry Reding, and Neal Sherry: The Garrison-Hot Springs estimated line load current for an outage of the Hot Springs-Ovando 230-kV line is calculated via a post contingency/pre-contingency ratio derived from off line power flows, studying worst case conditions.

For the Garrison-Hot Springs 230-kV line, the estimated line load current is equal to the actual line load current multiplied by a factor of 1.67. Equation (9) is the basic temperature rise for the conductor. The operating temperature of the conductor (Thermal limit, 100° C) minus the actual conductor temperature is the temperature rise to the Thermal limit. Using equation (9) and solve for Δt (time to Thermal limit) where ΔT is the temperature rise to the Thermal limit and I is the estimated current.

Manuscript received September 10, 1985.