# SYSTEM CONTINGENCY MONITORING
# USING LINE THERMAL RELAYING

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Presented at the

Western Protective Relaying Conference

October 28, 1980 in

Spokane, Washington

## I. ABSTRACT

Comprehensive line thermal protection combining $I^2R$, ambient and solar heating conductor temperature estimation is discussed. Use of this estimate by a system dispatch computer via SCADA allows for monitoring whether an increase in line loading due to a specified contingency will result in tripping the protected line. Time to trip is also provided to help determine dispatcher response should the contingency occur.

## II. INTRODUCTION

The information presented herein follows the subject of transmission line conductor capacity from a discussion on the assumptions made in arriving at operating limits, to the design of the transmission network to remain within those limits in normal operation. Then a few words are included about "unused" capacity which results from simplistic "worst-case" ratings with a subsequent description of prior methods used at more important substations to ensure compliance with these limits in order to protect the conductor from overload damage. The next subject is the integration of the real-time factor of ambient temperature, with some mention of solar heating and wind cooling, into the conductor resistance heating equation. A method of accomplishing this integration at the line terminals using an electronic relay is described, as is a method of paralleling this integration at the System Operations Control Center (SOCC) via the SCADA (Supervisory Control and Data Acquisition) system using the SOCC dispatch computer. Limitations on the applicability of this method due to line length or complex fault protection systems are also discussed, followed by description of such an installation on the Utah Power & Light Company system. The final topic is that of expanding the calculations in the dispatch computer to include possible contingencies (loss of parallel lines due to fault, etc.), and their effects on important "weak-link" transmission line overloading. Examination of many contingency possibilities can be done by the computer on a fairly constant basis, with notification of the dispatcher occuring only when the anticipated result of a contingency moves the system into an undesirable operating condition, and an evaluation of the risk is necessary.

## III. CONDUCTOR RATING CALCULATIONS

The goal of the applicable section of the "Transmission Standards" manual at Utah Power & Light Company is to provide ratings for the various conductors used in the transmission system for several generalized cases, in order to allow system planning and system operating personnel to properly utilize existing facilities. The cases mentioned are "normal," "short period overload," "summer emergency" and "winter emergency." Each case has a prescribed set of assumptions of ambient temperature, time duration of overload, solar and wind factors and possible loss-of-life consequences. The rating selected for targeting of the line thermal protection relaying was that of "short period overload," (SPOL). This rating is the highest calculated for which no loss of life is expected, and therefore was felt to be the highest allowable rating without some specific human evaluation of mitigating circumstances. The assumptions for which the calculations were made are shown in Table 1:

TABLE 1 SPOL ASSUMPTIONS

| | |
|---|---|
| Ambient temperature: | 40°C |
| Average solar heating: | 9°C |
| Critical conductor temperature: | 90°C |
| Time period from no-load to critical temperature: | 4 hours |

The resulting rating for each conductor considered was then presented in three phase MVA, assuming 1 per unit voltage, since blocks of power transfer are usually thought of in MVA, rather than amperes. The 90°C critical temperature selection was based on the 93°C annealing temperature of copper and the loss of life criterion.

The form of the calculation is presented below, with an explanation of terms:

eq. 1

$$I = \sqrt{\frac{\left[1.01+0.371\left(\frac{D\rho_f V}{\mu_f}\right)^{0.52}\right]k_f(tc-ta)+0.138D\varepsilon\left[\left(\frac{Kc}{100}\right)^4-\left(\frac{Ka}{100}\right)^4\right]-a(Q_D\sin\theta+Q_d)A'}{r}}$$

and:

$$\theta = \cos^{-1}[\cos H_c \cos(Z_c - Z_1)]$$

where:

$r$ - effective ac resistance, ohms/ft

$D$ - conductor diameter, inches

$\rho_f$ - air density, lb/cu ft

$V$ - air velocity ft/hr

$\mu_f$ - absolute viscosity of air, lb-mass/ft-hr

$k_f$ - thermal conductivity of air, (watts)(ft)/(ft$^2$)(°C)

$t_c$ - conductor temperature, °C

$t_a$ - ambient temperature, °C

$\varepsilon$ - thermal-emissivity constant

$K_c$ - conductor temperature, °K

$K_a$ - ambient temperature, °K

$a$ - solar absorption coefficient

$Q_D$ - direct solar radiation

$Q_d$ - sky radiation

$A'$ - projected area of the conductor

$H_c$ - altitude of the sun above the horizon

$Z_c$ - azimuth of the sun

$Z_1$ - azimuth of the conductor

Typical values for two conductor types are shown in Table 2. The first is commonly used on our latest 345 kV backbone lines, while the second is used on a much older 138 kV system which will be the topic of the subject relaying and contingency evaluation systems.

TABLE 2 TYPICAL CONDUCTOR RATINGS

| | | MVA RATINGS | | | |
|---|---|---|---|---|---|
| | DESCRIPTION | Normal | SPOL | Summer Emerg. | Winter Emerg. |
| 1. | 2-1272 MCM ACSR | 1397 | 1724 | 1840 | 2121 |
| 2. | 250 Copper | 126 | 151 | 163 | 185 |

## IV. TRANSMISSION NETWORK DESIGN

This subject has traditionally been the primary protection against thermal overload of lines, within single contingency criteria. That is, the number and capacity of transmission lines have been selected with a reserve capability for use when a parallel line is lost due to fault, tower failure or tripping error. If more than one event occurs, however, or in some specific cases where unusual configurations of generation interconnection occur temporarily due to delay or deferral of line construction, the actual transmission network may not be self-protective against thermal overload. Backup protection has been supplied by the transmission line fault protection relays for these other cases, but some inadequacies of this method will be discussed in the next section.

As a consequence of construction delay, project deferral, and generation projects inside and outside of the Company's service area, "weak-links" in Utah Power & Light Company's power transfer network have developed and have been detected by system planning and operating studies. The weakness is, of course, a direct function of the thermal capability of the affected transmission lines, and investigation was begun into the reasonability of the traditional limits mentioned in Section III. The first items to be examined were the assumptions which form the basis for the SPOL calculation. In several cases, special ratings had been approved on the basis of winter ambient temperature versus the 40°C assumption, since the overload probability was related to the winter peak, and since construction of additional line capacity in progress was expected to be complete prior to the next summer peak. In other cases, the overload probability was seen to be highest in the early morning hours prior to sunrise, and special ratings were given to allow maximum import of less expensive power from outside the Company.

As these special cases have become more and more numerous, each having some effect on the line protection relay settings, a need for a flexible ambient temperature related capacity determination has been recognized. The satisfaction of this need and the limitations of its effectiveness are discussed in the next section.

## V. PROTECTION METHODS

In the past, the need for thermal overload protection was relegated to whatever might result after primary and backup line fault protection needs were satisfied. In very many cases, no specific thermal protection was required, since fault relays had to be set to pick up at or below the SPOL rating in order to see far end fault currents. Simple overcurrent relays, which do not distinguish between fault and load current, used on lines of some length which have relatively low far end fault currents, leave no opportunity for taking advantage of "unused" capacity during periods of low ambient temperature. On shorter lines, however, far end fault current level may be significantly above SPOL current. Here "unused" capacity could be exploited during cooler times.

More sophisticated "impedance" based relays used on subtransmission and above were designed expressly to distinguish between "inductive" fault current and "resistive" load current. This enables sensitive tripping of far end fault currents, while allowing much higher, good power factor load currents to flow. In fact, for an overload condition characterized by unity power factor, impedance relays may provide no thermal protection at all. In these cases, on the Utah Power & Light Company system, a single phase overcurrent with a long timer setting is usually provided to guard the conductor. The pickup setting of this overcurrent relay is nominally the SPOL current for the least capable portion of the line conductor, assuming nominal voltage level.

On the vast majority of lines within a system, then, the pickup setting of a simple overcurrent relay is sufficient to protect the conductor, but in a few weak-link cases, automatic setting change as a function of ambient temperature could be of great benefit. A relay with this and other features was being marketed by the Sangamo organization, the design being provided by their European parent company, Schlumberger. The manufacture of the relay itself, in fact, is still done in Europe, but may be supplemented in the United States or Canada. Some unusual packaging characteristics (rear connected, projection mount only) might be normalized if this occurs. The identifying acronym for the relay is PSLS, with at least two style numbers. For the time being, however, PSLS will suffice. In addition to a single phase over-current input, the PSLS also monitors a platinum wire resistance versus temperature probe located in a wooden meteorological cabinet which, at Utah Power & Light Company, is located on the north outside wall of the substation control building. The PSLS electronics take the form of an integrator over time, following an exponential curve to estimate conductor temperature in degrees centigrade. Alarm and trip settings are in °C, rather than current level. The inputs, outputs, methods and ranges of the PSLS are presented in Table 3.

TABLE 3. PSLS INPUTS AND OUTPUTS

| Inputs and Outputs | Method | Range |
|---|---|---|
| Line current | Secondary current | 0-10 amp |
| Ambient temp. | Resistance probe | -10 to +40°C |
| Solar radiation | Dial setting | 0-20°C |
| Time constant | Plug in links | 10-20 minutes |
| Line heating | Dial setting | 0-50°C |
| Alarm selection | Dial setting | 0-80°C |
| Trip selection | Dial setting | 0-100°C |
| Alarm output | 2 form C contacts | N/A |
| Trip output | 2 form C contacts | N/A |
| Conductor temp. | Loop current for telemetry and small milliammeter in relay | 0-10 madc/0-100°C |

The correlation in use at Utah Power & Light Company to determine setting philosophy for this flexible relay follows a relatively logical procedure. SPOL is still the basis for tripping the line, and its limit of 90°C is distributed to extract "line heating" due to current flow by subtracting the 40°C ambient and 9°C solar heating assumptions, leaving 41°C as the temperature to which resistive heating would eventually bring the conductor on a dark, 0°C night with SPOL current flowing. Wind effect has been ignored thus far, so it should be explained that its cooling effect is reserved as "margin." That is, due to wind, the relay will always read a higher temperature than that of the actual conductor. Even on a still day, a warm conductor will self-generate enough convection to provide suitable margin. Selection of a time constant is less scientific, since little published data has been located to date. Therefore, the fastest rate, 10 minutes, is in use. This setting provides ample response time in Utah Power & Light Company's opinion, between an alarm setting at 80°C, and a trip setting at the 93°C annealing temperature. Security against tripping on through faults well in excess of SPOL is excellent, having been tested extensively on Utah Power & Light Company's model power system. Trip eventually results, but the time delay is well beyond the fault relaying, and while it might prevent conductor damage, it would certainly allow the arced-over component to be destroyed.

The use of these settings provides, then, that on a "worst-case" day, the conductor will be protected. The temperature is measured only at one end of the line, but logs of temperature recorded in the northern and southern divisions of our system show only a small disparity, and the single-ended risk is felt to be acceptable.

What benefit in "unused" capability results from use of the PSLS? This question can be answered by looking at some specific examples. The PSLS relates line heating to line current in approximately the intuitive $I^2R$ manner. That is, if the current doubles, the heating quadruples. Actually, an exponent of slightly greater than two is characteristic of the PSLS, as will be seen in later examples. For now, using 2.3 as the exponent, it can be calculate that on a 20°C ambient day, the allowable rating of a conductor is increased to 118.8% SPOL. This is done by computing the current heating increase allowable due to the ambient reduction (40°C - 20°C) below SPOL assumption using the following equation:

$$\% \text{ SPOL} = 100 \times \text{anti-log}\left(\frac{\log\left(\frac{41°\text{C} + (40°\text{C} - \text{A}°\text{C})}{41°\text{C base}}\right)}{2.3}\right) \qquad \text{eq. 2}$$

where:

A = ambient temperature

Later, in evaluating the time response of the conductor to changes in current flow, the mathematical nature of these relationships will be exploited to predict the effects of imagined contingencies.

## VI. INSTALLATION DESCRIPTION

A "weak-link" exists on Utah Power & Light Company's transmission system between the Ben Lomond and Wheelon Substations. It was decided that PSLS relays on the three 138 kV lines north from Ben Lomond could be used to take advantage of unused available capacity since peak loading occurs during the early morning hours when the ambient temperature is low.

The installation consisted of one PSLS 1200 master relay and two PSLS 1100 slave relays. Because of the master slave arrangement the relays share a common temperature probe. The problems presented by the relays unusual packaging were easily overcome. The mounting was changed from projection to semiflush by the use of standoffs. Since the relay is not a draw-out case style, each relay d-c supply was fused separately, and shorting type current knife switches were used so the relay could be tested in place.

Initially the relay was bench tested, for two reasons. First, since the relay was of French manufacture, not much technical information was available. The relay response to separate inputs and to input variations was noted during the initial test. This provided valuable information into relay functions and also suggested further uses for the relay. Second, the test showed that the relay would operate satisfactorily from a component reliability standpoint, and that it was secure from misoperation on faults or noise.

After the relays were installed and set at the substation, test equipment consisting of a variable current source, a voltage source, a variable resistor and timers, was set up to verify the settings. The first step in the test procedure was to apply voltage and allow the relay to reach the total of solar setting (9°C) and the SPOL ambient temperature (40°C) applied by the variable resistor. Next, a secondary CT current representing 160 percent SPOL line current was applied. The times to alarm and trip were measured and adjustments were made to obtain the proper settings.

As a final check, the actual conductor temperature was compared with the relay modeled temperature. This was accomplished by use of an AGA Thermovision 750 camera. The equipment was originally purchased and mounted on a van to locate system hot spot problems but also has the capability of measuring temperature rise above a known reference, which made it ideal for this use. At the time of comparison the load was down but the relay modeled a conductor temperature of 12.6°C. The thermovision 750 measured a temperature of 11-12°C. The difference between the two readings was attributed to the three mph wind present which as mentioned is used as safety margin by the relay. These measurements will be repeated in the future during heavier load periods.

The PSLS relay has 2 C-form contacts with 0-80°C variable pickup for alarming. Utah Power & Light Company chose the 80°C alarm point to minimize the alarms and connected this to the substation annunciator.

Also available are two C-form contacts variable from 0-100°C for tripping. Utah Power & Light Company chose to set the pickup point at 93°C. One contact was used to trip the circuit breaker protecting the line. The other was used to block the close circuit of the breaker. This works well since it takes from one to one and one-half minutes for the relay to reset the trip contacts, which allows a recloser relay to go to lockout.

The manufacturer provided an output for a remote auxiliary temperature meter. This output is located in series with the display meter in the relay's zero to ten milliamp current loop used to produce the 0-100°C readings. By placing a 500 ohm resistor across this output a zero to five volt signal can be produced to represent conductor temperature. This signal is then be sent via SCADA to SOCC. Thus the PSLS is not only a relay but also a temperature transducer.

## VII. CONTINGENCY MONITORING

Briefly, SOCC consists of two TRW Sigma 5 computers and four dispatcher's consoles. One computer is used on-line for operational control and the other is on-line backup. Other computers perform functions such as load management. All incoming signals terminate directly below the computer room.

One of the products of Utah Power & Light Company's initial bench test was an empirically derived curve as shown in Figure 1. Since the computer was designed for mathematical modeling, curve fitting was employed to try to describe the relay curve mathematically. The equation arrived at is:

$$°C = 41I^{2.3} \left(1 - e^{-\frac{T}{\tau}}\right) \qquad \text{eq. 3}$$

where

$\tau$ = relay time constant setting

41 = SPOL line heating temperature

T = time in minutes

I = % SPOL line current

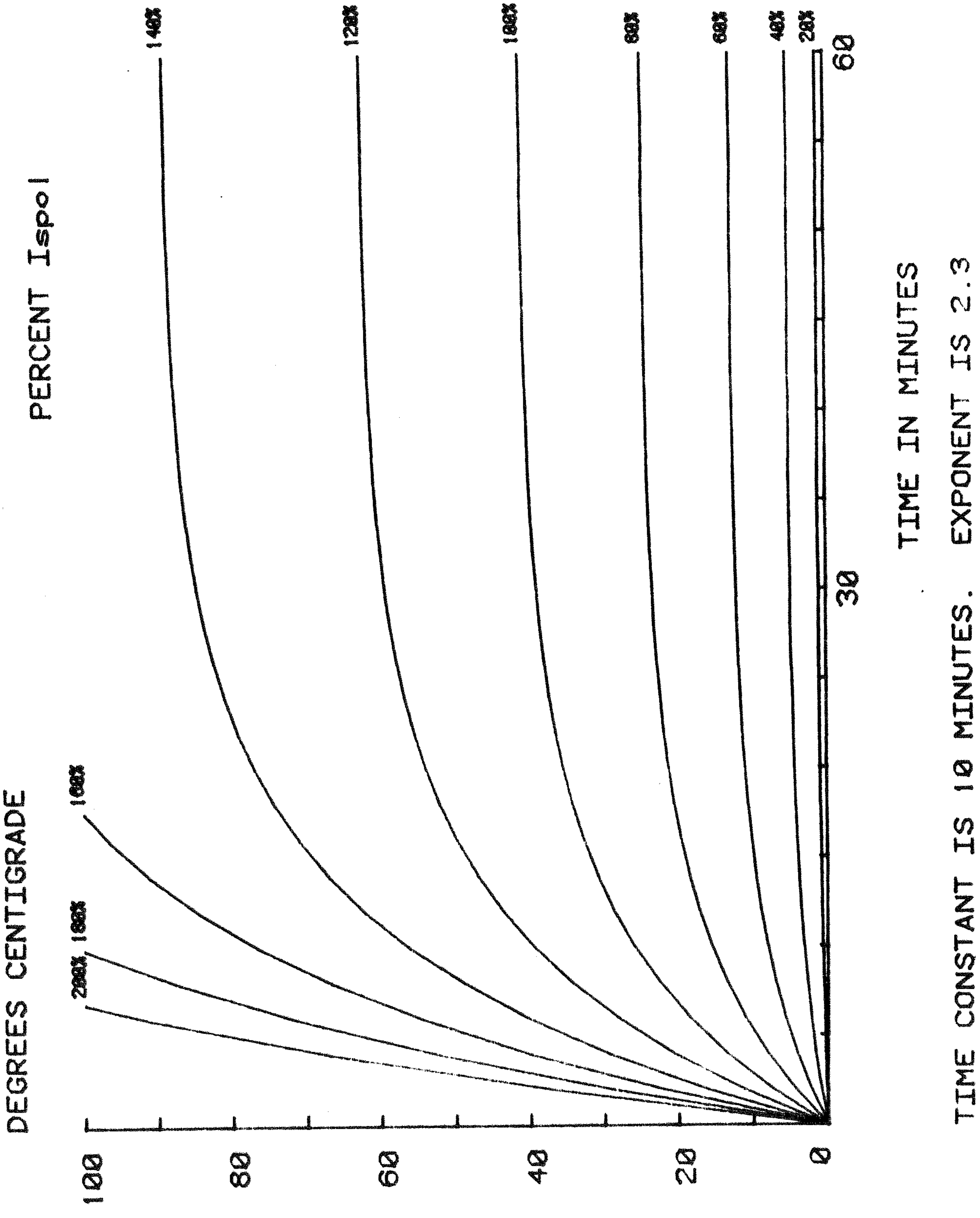


FIGURE 2. EMPIRICALLY DERIVED RELAY CURVE

Equation 3 is based on the $I^2R$ heating relationship except that the relay response is at 2.3 power unstead of squared. This equation can be rearranged in the form:

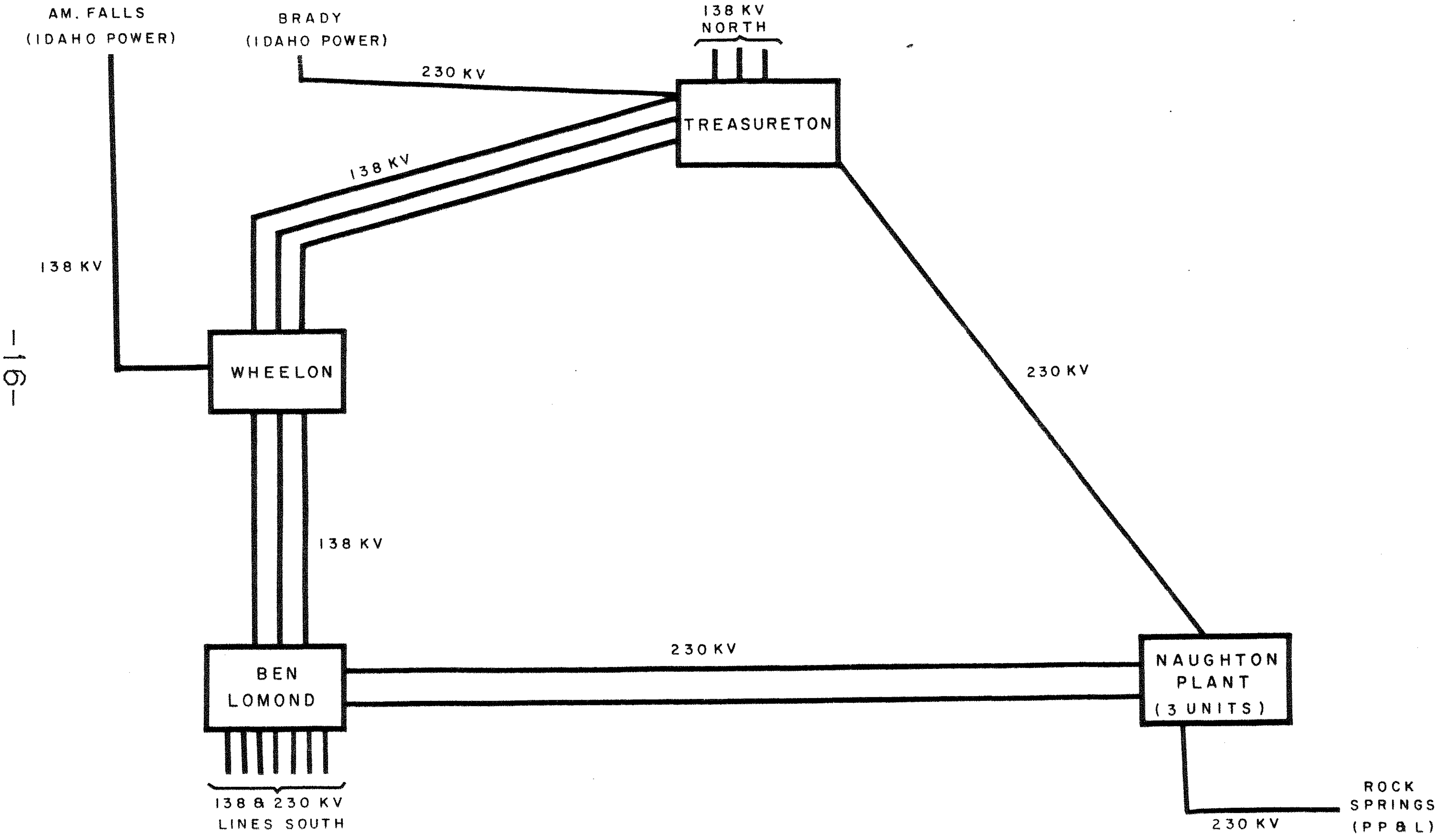
$$T = - \tau \ln \left( 1 - \frac{°C}{41I^{2.3}} \right) \qquad \text{eq. 4}$$

Using this equation, the computer can calculate the time required to reach a given temperature. By subtracting the calculated "start" time for the telemetered conductor temperature at Ben Lomond Substation using the present line current, from the calculated "finish" time of the relay trip temperature, 93°C, a time, which represents the time remaining to trip at some higher current can be found. This time becomes especially important to Utah Power & Light Company's dispatchers because of the present situation on the northern transmission system.

Figure 2 shows a single line diagram of this portion of the Utah Power & Light Company system. Briefly, one 230 kV line connects the three Naughton generators to Treasureton Substation. Naughton is also connected to Pacific Power & Light Company's system by a 230 kV line to Rock Springs and to Ben Lomond by two 230 kV lines. Ben Lomond then connects to Wheelon by three 138 kV lines. This is the "weak-link" the PSLS relays protect. Wheelon completes the loop to Treasureton by three 138 kV lines. Wheelon and Treasureton Substations have 138 kV and 230 kV tie lines respectively to Idaho Power. Treasureton feeds the northern system load through Goshen Substation.

Pacific Power & Light Company operates a 345 kV line from the Jim Bridger Station across the north part of Utah Power &

FIGURE 2. TRANSMISSION SYSTEM



Light Company's system tying into Goshen Substation. Under heavy load conditions or if one of the Pacific Power & Light Company's 345 KV lines trip, Jim Bridger tries to push power across Utah Power & Light Company's system; part of which flows across the Ben Lomond-Wheelon "weak-link." If the Naughton-Treasureton 230 kV line trips, 54 percent of its load shifts to the Ben Lomond-Wheelon "weak-link." Either of the above contingencies can cause a thermal overload of this "weak-link" and loss of Utah Power & Light Company's northern customers.

Using the time remaining to trip, the dispatcher is warned if a load or contingency situation exists that would exceed the thermal limits of this "weak-link." The amount of time he has to correct the impending trip is also displayed on the computer terminal. This information level makes risk management much easier for the dispatchers. These calculations also provide the amount of reserve capacity available to aid proper scheduling.

A flow chart of the algorithm used to make these calculations is attached in Appendix I.

Other installation sites on Utah Power & Light Company's system include the Carbon-Ashley 138 kV tie line, Sigurd-Glen Canyon 230 kV tie line, Rigby-Goshen 161 kV line and the Rigby-Sugarmill 161 kV line. The last two installations are system weak-links similar to Ben Lomond-Wheelon. Future installations include any tie lines or system weak-links that are loaded near their thermal limit where the far end fault current is significantly above the thermal limit of the line.

There also exists the possibility of installing a temperature probe and transducer at a substation, telemetering this data to the SOCC computer and thermally protecting a line by means of a computer algorithm. This could also be accomplished using a microprocesser at the substation. Cost savings and curve flexibility are the major advantages for the probe-computer approach. The disadvantage of using telemetered data is the absence of a local backup thermal line relay.

## VIII. OPERATING EXPERIENCE

Utah Power & Light Company's Planning Department had predicted a significant increase in loading on the Ben Lomond-Wheelon 138 kV lines, however, the actual peak loading this summer was less than last year. The reasons for this were: 1) Jim Bridger power station was only generating 1400 of their 2000 megawatt capacity, 2) the northwest utilities experienced a very wet water year and 3) Utah Power & Light Company's summer load was lower due to a relatively mild summer. The PSLS thermal relays were still very useful, however. Utah Power & Light Company experienced an increased scheduling capacity, which meant that the line loss contingency, generator dropping scheme at Naughton was never armed and the expense and risk of dropping a unit was prevented. It also meant that the power scheduled across the Utah Power & Light Company system could be increased, generating more revenue.

## IX. SUMMARY

A rough approximation of conductor temperature, gained by considering ambient temperature and using wind as safety margin, can be obtained with relatively simple electronic devices. This approximation provides 34% more conductor capability, at 0°C ambient, than a fixed "worse-case" temperature rating. Seasonal rating changes are made automatically, and rating data can be derived for nearly any load contingency by calculating according to a simplified relationship, modeled by the relay described herein. In the future, serious consideration will be given to replacing all "worst-case" transmission line conductor ratings with a constantly changing approximation using ambient temperature. This approach seems to be an excellent compromise between the fixed "worst-case" method and the much more sophisticated implanted detector in the energized conductor, with data transmitted dielectrically to a control unit at ground potential.

# REFERENCES

1. "Current-Temperature Characteristics of Aluminum Conductors," Alcoa Conductor Engineering Handbook - Section 6, Alcoa Conductor Products Company, Pittsburgh, Pennsylvania.

2. Davis, M., "A New Thermal Rating Approach: The Real Time Thermal Rating System for Strategic Overhead Conductor Transmission Lines," Part I and Part II, IEEE Trans., Power Apparatus and Systems, Vol. PAS-96, No. 3, pp 803-825, May/June 1977.

3. House, H. E. and Tuttle, P. D., "Current Carrying Capacity of ACSR," AIEE Transactions, Paper 58-41, February, 1958.

4. "Line Thermal-Overload Relay for High and Medium Voltage Lines," Technical Note 322-011, Power Protection Group, Sangamo-Weston Instruments, Inc., Atlanta, Georgia.

# APPENDIX 1

## THERMAL CONTINGENCY

## FLOW CHART KEY

C1 - Ben Lomond 103 line conductor temperature

C2 - Ben Lomond 104 line conductor temperature

C3 - Ben Lomond 105 line conductor temperature

C5 - Line heating portion of conductor temperature for hottest line

C7 - Ambient temperature

C9 - Contingency final line heating temperature

M2 - Hottest conductor megawatt load

M4 - Naughton-Treasureton megawatt load

M5 - Ben Lomond-Wheelon contingency megawatt load

I2 - Hottest conductor line current

I5 - Contingency line current

T1 - Start time on contingency relay curve

T2 - Alarm time on contingency relay curve

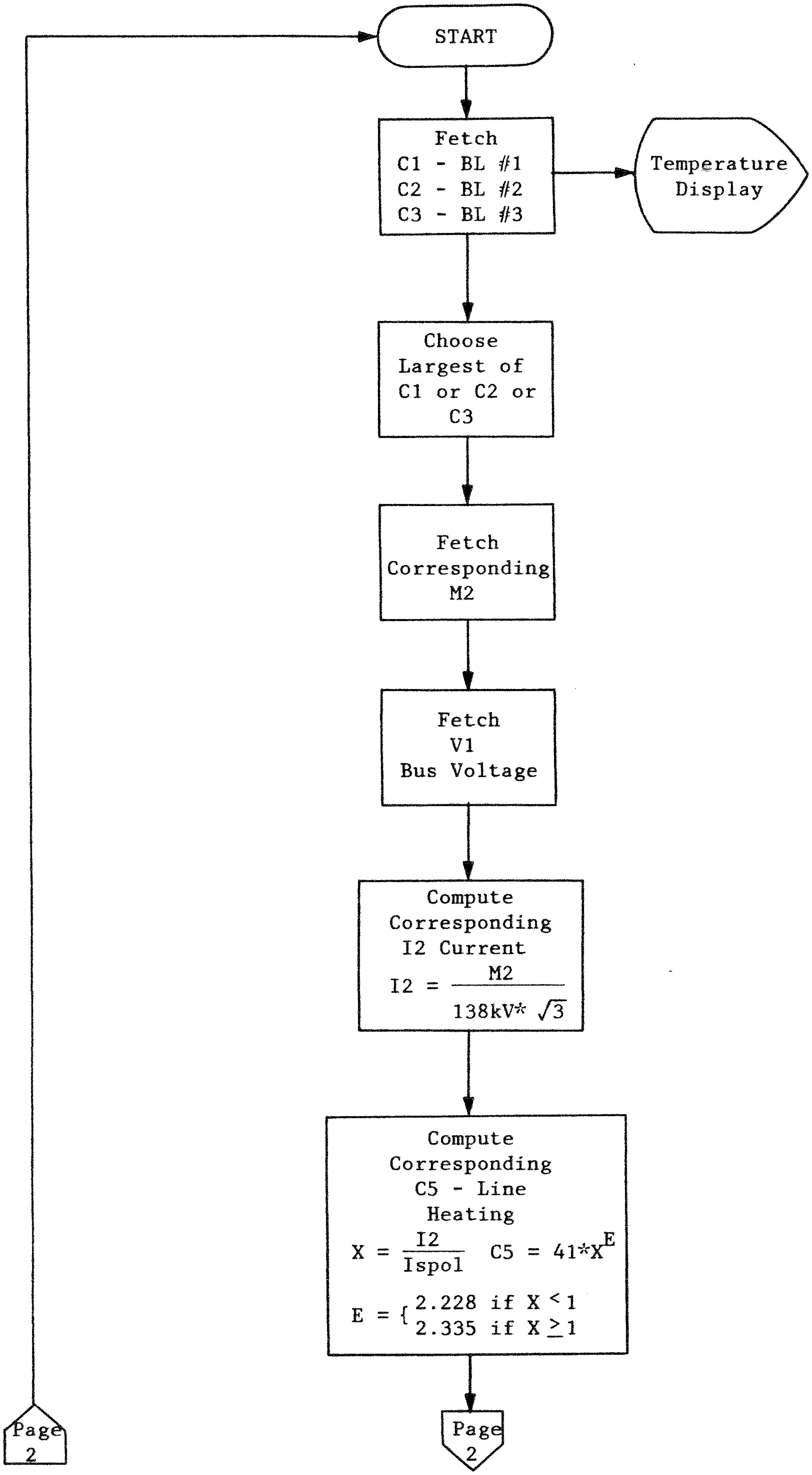
T3 - Trip time on contingency relay curve

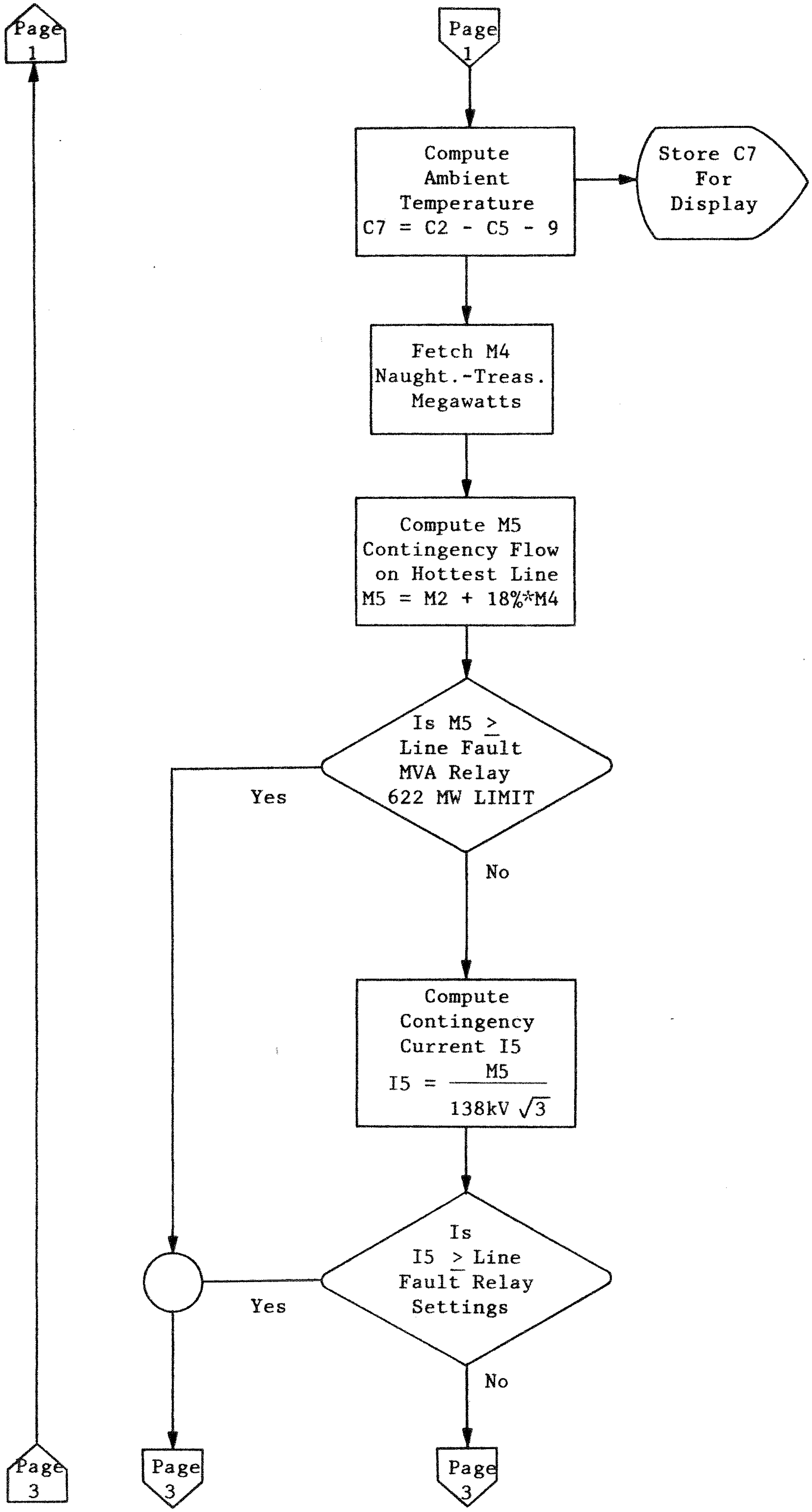
V1 - Ben Lomond 138 kV bus volts

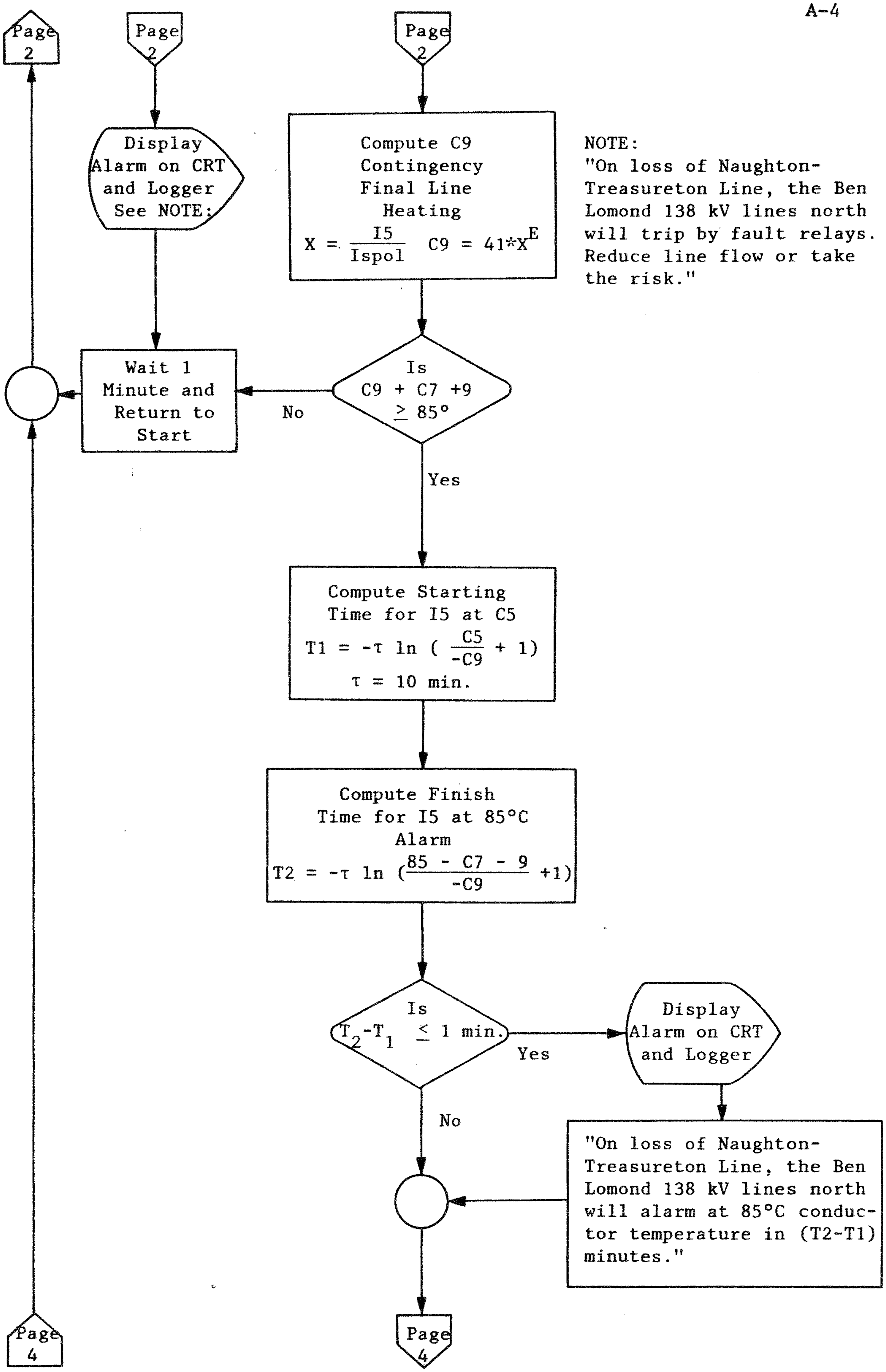
E - Power to raise X to (between 2 and 3) for best curve fit

X - Ratio of line current to $I_{SPOL}$

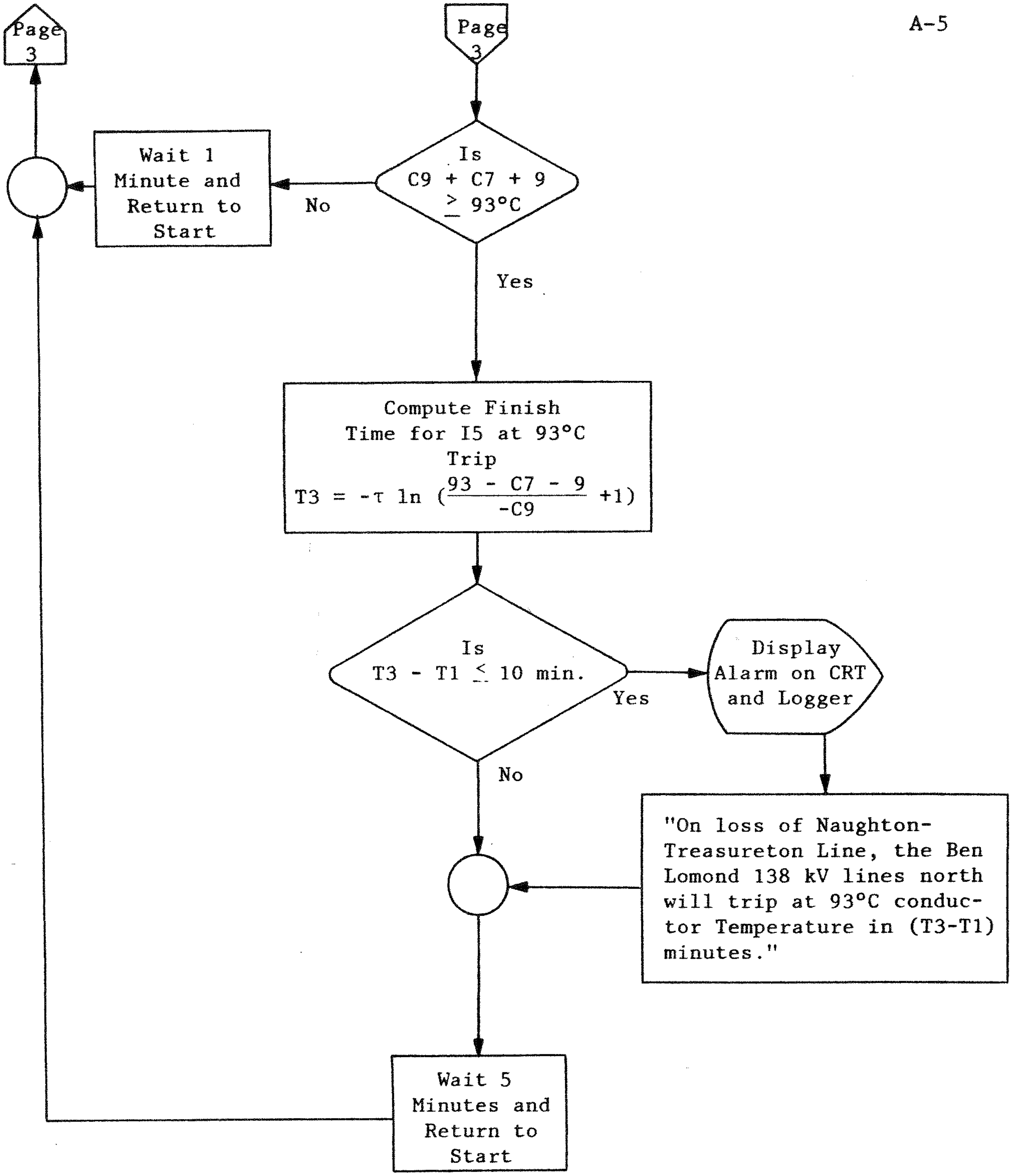
# BEN LOMOND THERMAL CONTINGENCY FLOW CHART




Page 1
Page 1
Compute Ambient Temperature C7 = C2 - C5 - 9
Store C7 For Display
Fetch M4 Naught.-Treas. Megawatts
Compute M5 Contingency Flow on Hottest Line M5 = M2 + 18%*M4
Is M5 ≥ Line Fault MVA Relay 622 MW LIMIT
Yes
No
Compute Contingency Current I5
I5 = M5 / 138kV √3
Is I5 ≥ Line Fault Relay Settings
Yes
No
Page 3
Page 3
Page 3



NOTE:
"On loss of Naughton-Treasureton Line, the Ben Lomond 138 kV lines north will trip by fault relays. Reduce line flow or take the risk."


Page 3
Page 3
Is C9 + C7 + 9 ≥ 93°C
No
Wait 1 Minute and Return to Start
Yes
Compute Finish Time for I5 at 93°C Trip
$T3 = -\tau \ln \left(\frac{93 - C7 - 9}{-C9} + 1\right)$
Is T3 - T1 ≤ 10 min.
Yes
Display Alarm on CRT and Logger
No
"On loss of Naughton-Treasureton Line, the Ben Lomond 138 kV lines north will trip at 93°C conductor Temperature in (T3-T1) minutes."
Wait 5 Minutes and Return to Start