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ABSTRACT

This paper reviews the basic mathematical and physical principles of line thermal protection and presents the implementation of this element into a transmission line relay with advanced programmable logic capabilities. This type of protection is particularly useful when the load current carried by the line is close to the conductor ampacity limit.

Keywords: cable ampacity, protective relays, thermal element, thermal protection, transmission line thermal protection.

INTRODUCTION

Line thermal protection consists of monitoring the conductor temperature and generating a trip signal when the temperature becomes greater than the conductor maximum allowed temperature. The temperature is not measured directly but is emulated using a first-order thermal model. The conductor temperature is determined by establishing the heat-balance equation (heat input minus heat losses) of a conductor section 1000 feet in length. It is assumed that this section of the line is the hottest and it has been exposed to the maximum solar radiation. Heat input to the conductor is mainly due to heat dissipated in the conductor resistance and to solar heat gain. Heat losses are mainly due to convection and radiation losses. All of these principles and procedures have been standardized in the document IEEE Std 738-1993 "IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors" [1] and the basic physical equations are summarized in [2].

The absence of proper line thermal protection could lead to catastrophic events. Thermally overloaded lines will develop excessive sag. The conductors' sag in turn will increase the risks of faults from contact with nearby objects. Early reports indicated that this very scenario could have been one of the root causes that led to the North American blackout of August 2003.

This paper describes the implementation of the heat-balance equation as a first-order thermal model and the temperature rise equations using user-friendly programmable logic with mathematical capabilities in addition to conventional Boolean operations.

THE THERMAL MODEL OF A LINE CONDUCTOR

The mathematical and physical background of first-order thermal models is thoroughly explained in the Annex of [3].

Refer to Table 1 for the definition of model variables.

Table 1 First-Order Thermal Model Variables

Variable	Definition	Unit
P	heat power input to the conductor	kW/kft
THC	conductor heat thermal capacity	kJ/°C kft
TRA	thermal resistance to ambient	°C kft/kw
TC	estimated conductor temperature	°C
TA	ambient temperature	°C
TI	conductor initial temperature	°C
I	conductor current	A RMS
R_{ac}	AC conductor resistance at 25°C	Ω/kft
R_{delt}	temperature coefficient of AC resistance	Ω/°C kft
Q_{sun}	heat power input from the sun	kW/kft
$Q_{radiated}$	radiation heat losses	kW/kft
$Q_{convected}$	convection heat losses	kW/kft
ΔT	processing interval or integration step	s

The equation of the line conductor temperature is expressed as a first-order differential equation:

$$\text{Power supplied to the conductor or } P - \text{Losses} = \text{THC}\frac{d\,TC}{d\,t} \tag{1}$$

The heat power supplied to the conductor is expressed as

$$P = I^2 \bullet \left[R_{ac} + (TC - 25) \bullet R_{delt}\right] + Q_{sun} \tag{2}$$

and the conductor heat losses can be expressed as

$$\frac{TC - TA}{TRA} = Q_{radiated} + Q_{convected} \tag{3}$$

The conductor temperature differential equation is then

$$\text{THC}\frac{d\,TC}{dt} = I^2 \bullet \left[R_{ac} + (TC - 25) \bullet R_{delt}\right] + Q_{sun} - \frac{TC - TA}{TRA} \tag{4}$$

so that the solution for the conductor temperature is provided by

$$TC(t) = \int_0^t \left[\frac{I^2 \bullet \left[R_{ac} + (TC - 25) - R_{delt}\right] + Q_{sun}}{THC} - \frac{TC - TA}{TRA \bullet THC}\right] dt + TI \tag{5}$$

This equation can be solved numerically by computing the conductor temperature increment (ΔTC) at each processing interval

$$\Delta TC = \left[\frac{I^2 \bullet \left[R_{ac} + (TC - 25) \bullet R_{delt} \right] + Q_{sun}}{THC} - \frac{TC - TA}{TRA \bullet THC} \right] \Delta T \tag{6}$$

and by computing iteratively the new conductor temperature:

$$TC_{new} = \Delta TC + TC_{old} \tag{7}$$

At the first iteration, the conductor temperature is given the value of the initial conductor temperature:

$$TC_1 = TI \tag{8}$$

For the following iterations, the conductor temperature is calculated by computing iteratively the temperature increment using Equation (6) and then by processing the sum in Equation (7) that provides the estimated conductor temperature.

The line thermal protection can be represented as a first-order thermal model for the conductor temperature, as provided in Figure 1. In this figure, TTH is the maximum allowable temperature threshold above which the line could be tripped. TTL is an alarm threshold.

The conductor temperature time variation equation, when the conductor current (I) is a step function and Q_{sun} is assumed to be constant is provided by

$$TC(t) = P \bullet TRA \left[1 - \exp\left(- \frac{t}{THC \bullet TRA} \right) \right] + TA \tag{9}$$

When t becomes infinite, the conductor temperature becomes

$$TC = \frac{\left[I^2 \bullet (R_{ac} - 25 \bullet R_{delt}) + Q_{sun} \right] \bullet TRA + TA}{1 - I^2 \bullet R_{delt} \bullet TRA} \tag{10}$$

Assuming a conductor maximum temperature (TTH) the maximum current allowed on the conductor or its ampacity before the maximum temperature will be reached is

$$I = \sqrt{\frac{TTH - TA - Q_{sun} - TRA}{\left[R_{ac} + (TTH - 25) \bullet R_{delt} \right] \bullet TRA}} \tag{11}$$

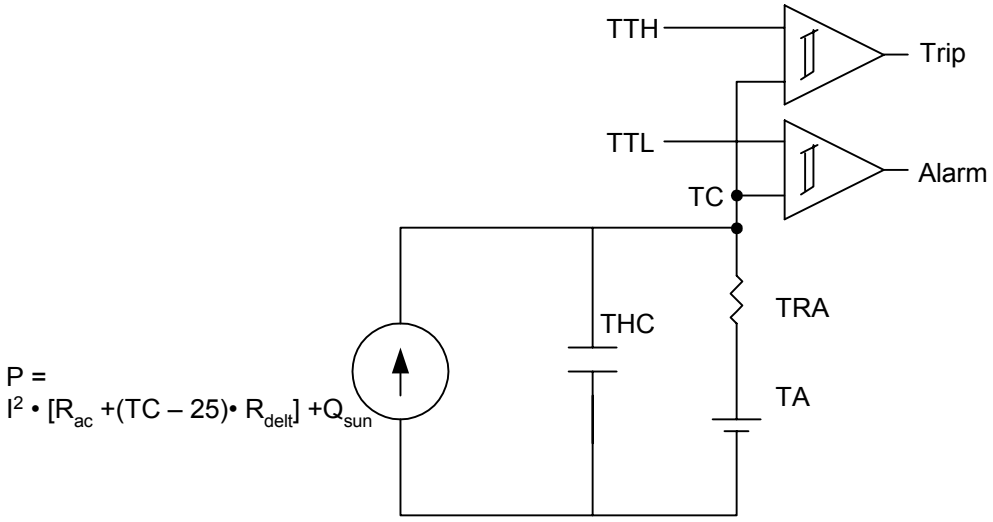

Figure 1 First-Order Line Thermal Model

COMPUTATION OF Q_{SUN}

The heat power input (Q_{sun}) on the conductor is a function of the conductor longitude and latitude, the day of the year, and the local time. The methodology to compute Q_{sun} is provided in [4].

Refer to Table 2 for definitions of the variables used in the computation of Q_{sun}.

Table 2 Variables Used in the Computation of Q_{sun}

Variable	Definition	Unit
d	solar declination	degrees
n	day of the year	days
Hrs	local time in hours	hours
LocT	local time	degrees
Ws	solar time	degrees
SAC	solar absorption coefficient	unitless
DIA	conductor diameter	inches
z	solar zenith angle	degrees
LSTD	standard time meridian	degrees west longitude
LON	conductor longitude	degrees west longitude
LAT	conductor latitude	degrees north latitude
SIR	solar incident radiation	kW/in
Q_{sun}	solar heating	kW/kft

The heat power striking the conductor from the sun is provided by the next equation:

$$Q_{sun} = SAC \bullet DIA \bullet SIR \tag{12}$$

The solar incident radiation (SIR) is provided by way of the look-up table as a function of z, the zenith angle. This look-up table is shown in Table 3.

The solar zenith angle is provided indirectly by way of its cosine as a function of the solar declination (d) the conductor latitude (LAT) and the solar time (Ws) as:

$$\cos(z) = \sin(d) \bullet \sin(LAT) + \cos(d) \bullet \cos(LAT) \bullet \cos(Ws) \tag{13}$$

We can, in an easier fashion, implement a polynomial approximation of a look-up table rather than putting it into the program. Based on this principle and the look-up table of Table 3, the plot of SIR as a function of the cosine of the solar zenith angle (z) is shown in Figure 2. A polynomial regression analysis allows fitting a polynomial of order 5 to approximate the function. The polynomial coefficients are shown in Figure 2. The solar incident radiation can then be computed using the next equation:

$$SIR = a_5 \bullet \cos(z)^5 + a_4 \bullet \cos(z)^4 + a_3 \bullet \cos(z)^3 + a_2 \bullet \cos(z)^2 + a_1 \bullet \cos(z)^1 + a_0 \tag{14}$$

Power n of cos(z) can be simply computed by multiplying cos(z) n times by itself.

The solar time (Ws) is provided as a function of the local time (LocT) the longitude (LON) and the standard time meridian (LSTD) as

$$Ws = LocT + (LON - LSTD) \tag{15}$$

The local time (LocT) is provided through a function of the local time expressed in hours (Hrs) as

$$LocT = (Hrs - 12) \bullet (-15) \tag{16}$$

Finally the solar declination (d) is expressed as a function of the day of the year (n) as

$$d = 23.45 \bullet \sin\left(\frac{284 + n}{365} \bullet 360\right) \tag{17}$$

The local time (Hrs) and the day of the year (n) are available inside the line relay as THR and DDOY. The conductor latitude (LAT) and longitude (LON) together with the standard time meridian (LSTD) have to be entered in the program as settings.

This solar model assumes no effect of clouds or shade. Hence the model calculates worst-case (maximum) heat input power from the sun. Clouds or shading will cause the estimated conductor temperature to exceed actual conductor temperature.

Table 3 SIR Value as a Function of z Look-Up Table

z	SIR
85	1808
80	3350
75	4516
70	5366
65	5958
60	6416
55	6791
50	7066
45	7283
40	7500
30	7741
20	7916
10	7983
0	8033

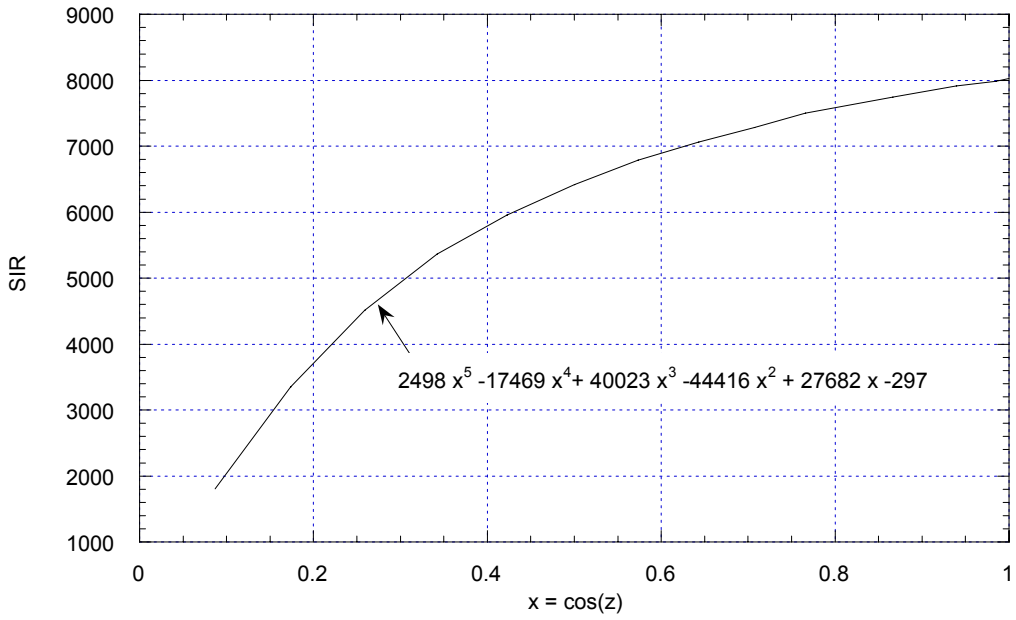

Figure 2 Relation Between SIR and the Cosine of the Zenith Time (z)

THE DETERMINATION OF THE CONDUCTOR THERMAL RESISTANCE (TRA)

The conductor thermal resistance is provided by Equation (3) and is equal to the required temperature difference between the conductor and the ambient so that the heat power transferred from the conductor is one unit of power.

$$TRA = \frac{TC - TA}{Q_{radiated} + Q_{convected}} \tag{18}$$

The conductor thermal resistance to ambient (TRA) can be computed by linearizing the heat losses across the difference between two temperatures. The conductor and ambient temperatures are the first and second temperatures. The formula is as follows:

$$TRA = \frac{\text{Conductor temperature} - \text{Ambient temperature}}{\text{Sum of convected and radiated heat losses}} \tag{19}$$

$$TRA = \frac{TC - TA}{\left[Q_{convected}(TC - TA) + Q_{radiated}(TC - TA)\right]} \tag{20}$$

The radiated heat losses are in turn computed as

$$Q_{radiated} = S \bullet E \bullet A \bullet \left(KC^4 - KA^4\right) \tag{21}$$

Where the variables are defined in Table 4.

Table 4 Variables in Equation (21)

Variable	Definition	Unit
S	Stephan-Boltzman constant = 0.5275e-8	$W/°K^4ft^2$
E	Thermal emissivity constant = 0.23 for new conductor = 0.91 for blackend conductor	unitless
A	area of circumscribing cylinder	ft^2
KC	conductor temperature	°K
KA	ambient temperature	°K

After adjusting the units, we end up with

$$Q_{radiated} = 0.138 \bullet DIA \bullet E \bullet \left[\left(\frac{KC}{100}\right)^4 - \left(\frac{KA}{100}\right)^4\right] \tag{22}$$

where DIA, the conductor diameter, is in inches and the units of $Q_{radiated}$ are in kW/kft.

The convected heat losses can be computed according to

$$Q_{convected} = \left[1.01 + 0.371\left(\frac{DIA \bullet R \bullet V}{H}\right)^{0.52}\right] \bullet K \bullet (TC - TA) \tag{23}$$

where the variables are defined in Table 5.

Table 5 Variables in Equation (23)

Variable	Definition	Unit
R	air density	lb/ft^3
V	air velocity	ft/hr
H	absolute viscosity	lb/hr ft
K	thermal conductivity	W/ft^2 °C

THE DETERMINATION OF THE CONDUCTOR THERMAL CAPACITY (THC)

The mass (m) of a body multiplied by its specific heat (C_s) is known as C, the thermal capacity of the system with units in kJ/°C. It represents the amount of energy in joules required to raise the system temperature by one degree Celsius.

In the case of a power conductor, the thermal heat capacity is simply determined by multiplying the number of pounds of aluminum (WA) by the aluminum-specific heat and adding the number of pounds of steel (WS) multiplied by the steel-specific heat:

$$\mathrm{THC} = \frac{\mathrm{WA} \bullet 428.8 + \mathrm{WS} \bullet 204.9}{1000} \tag{24}$$

SETTINGS

There are 18 settings that have to be entered into the line thermal relay algorithm. They must all be scaled to a per unit conductor length equal to 1000 ft. These settings can be broken into four groups: Solar Model Settings, Thermal Model Settings, Temperature Settings, and Logic Switches.

Solar Model Settings

Table 6 Solar Model Settings

Setting	Definition	Unit
DSH	default solar heating	kW/kft
SAC	solar absorption coefficient	unitless
DIA	conductor diameter	inches
LSTD	longitude of time standard	degrees west longitude
LON	longitude of conductor	degrees west longitude
LAT	latitude of conductor	degrees north latitude

The default solar heating (DSH) has to be set to some constant value if the sun radiated power Q_{sun} is not computed according to Equation (12) but introduced as a constant value equal to DSH.

The only purpose of entering the diameter (DIA) as a setting is to compute Q_{sun} as provided by Equation (12). In reality, a corrected diameter (DIA_{cor}) has to be entered in order to take into account the elevation and the atmosphere quality as in

$$DIA_{cor} = k_1 \bullet k_2 \bullet DIA \tag{25}$$

k_1 and k_2 must be chosen according to Table 7and Table 8.

Table 7 Values of k_1

Elevation (ft)	K_1
0	1.00
5000	1.15
10000	1.25
15000	1.30

Table 8 Values of k_2

Atmosphere	K_2
Clean	1.00
Industrial	0.82

The longitude of the time standard must be entered according to Table 9.

Table 9 Longitude of the Time Standard

Time Zone	Meridian
Eastern	75°W
Central	90°W
Mountain	105°W
Pacific	120°W

Thermal Model Settings

Table 10 Thermal Model Settings

Setting	Definition	Unit
R_{ac}	AC resistance at 25°C	Ω/kft
R_{delt}	temperature coefficient of AC resistance	Ω/°C kft
THC	thermal heat capacity	kJ/°C kft
TRA	thermal resistance to ambient	°C kft/kW

These four settings must be calculated from the conductor characteristic tables or the provided formulas. See the example below.

Temperature Settings

Table 11 Temperature Settings

Setting	Definition	Unit
EAT	estimated ambient temperature	°C
EOT	estimated offset temperature	°C
TTH	high temperature threshold	°C
TTL	low temperature threshold	°C
TI	conductor initial temperature	°C

If an external temperature sensor is not available, the estimated ambient temperature (EAT) must be entered. This will introduce errors into the thermal model because the ambient temperature is not measured but assumed to be equal to some value.

The estimated offset temperature (EOT) is the temperature difference between the ambient temperature available (introduced or measured) and the estimated hottest ambient temperature along the line. It must be entered as a number different from zero if it is estimated that the difference indeed exists. If not, it must be equal to zero.

The two thresholds (TTH and TTL) are used either to trip the line or to generate an alarm, respectively.

The initial temperature setting (TI) depends upon the line state at the moment the function will be started. If the line is open, TI can be given simply, by neglecting the impact of the sun, the value of the ambient temperature. If a current is flowing into the line, Equation (10) must be used to compute the conductor temperature, and this temperature becomes the initial temperature setting.

Note that the accuracy of the initial temperature setting is not critical because the conductor temperature will adjust itself within the time frame of the thermal model time constant.

Logic Switches

Table 12 Local Switch Settings

Setting	Definition	Logic States
THE	thermal trip enable	1/0
TSE	thermal sensor enable	1/0
SGE	solar generator enable	1/0

THE must be set to 1 if the line ought to be tripped due to excessive temperature.

TSE must be set to 1 if an external sensor is available for the ambient temperature. Otherwise, the ambient temperature is assumed to be equal to EAT.

SGE must be set to 1 if Q_{sun} is computed from Equation (12). It is set to 0 if Q_{sun} is introduced as being equal to a constant equal to DSH.

EXAMPLE OF IMPLEMENTATION

A line conductor is made of Drake cable type with the following basic characteristics that can be extracted from tables:

Diameter	DIA = 1.108 in (k1=k2=1.0)
Thermal emissivity constant	E = 0.5 (unitless)
AC resistance per mile at 25°C	RL = 0.117 Ω/mile
AC resistance per mile at 75°C	RH = 0.139 Ω /mile
Weight of aluminum 1000 ft of conductor	WA = 750 lb/kft
Weight of steel of 1000 ft of conductor	WS = 344 lb/kft

Determination of R_{ac}

The value of R_{ac}, the conductor resistance per 1000 ft, is determined from the value of RL:

$$R_{ac} = \frac{RL}{5.28} = \frac{0.117}{5.28} = 0.022159\ \Omega / \text{kft} \tag{26}$$

Determination of R_{delt}

The value of R_{delt}, the conductor temperature coefficient, is computed from

$$R_{delt} = \frac{RH - RL}{(75 - 25) \bullet 5.28} = \frac{0.139 - 0.117}{50 \bullet 5.28} = 0.0000833\ \Omega / °\text{C kft} \tag{27}$$

Determination of THC

The thermal heat capacity is determined by multiplying the number of pounds of aluminum (WA) by the aluminum-specific heat and adding the number of pounds of steel (WS) multiplied by the steel-specific heat:

$$\text{THC} = \frac{\text{WA} \bullet 428.8 + \text{WS} \bullet 204.9}{1000} = 392.086 \text{ kJ / °C kft} \tag{28}$$

Determination of TRA

TRA is computed using Equation (18) through Equation (23) and using a conductor temperature of 90°C and an ambient temperature of 40°C.

First, we compute the radiated power. From Equation (22), we have

$$Q_{\text{radiated}} = 0.138 \bullet \text{E} \bullet \text{DIA}\left[\left(\frac{\text{KC}}{100}\right)^4 - \left(\frac{\text{KA}}{100}\right)^4\right] \tag{29}$$

or

$$Q_{\text{radiated}} = 0.138 \bullet 0.5 \bullet 1.108\left[\left(\frac{363}{100}\right)^4 - \left(\frac{313}{100}\right)^4\right] = 5.937 \text{ kW/kft} \tag{30}$$

The convected power is computed from Equation (23) with the assumed air constants listed in Table 13.

Table 13 Assumed Air Constants

Variable	Definition	Value
R	air density	0.0752 lb/ft^3 (20°C, sea level)
V	air velocity	2 ft/sec = 7200 ft/hr
H	absolute viscosity	0.0439 lb/hr ft (20°C)
K	thermal conductivity	0.00784 W/ft^2 °C (20°C)

$$\begin{aligned} Q_{\text{conv}} &= \left[1.01 + 0.371\left(\frac{1.108 \bullet 0.0752 \bullet 7200}{0.0439}\right)^{0.52}\right] \bullet 0.00784 \bullet (90 - 40) \\ &= 20.964 \text{ kW/kft} \end{aligned} \tag{31}$$

Finally, we have for TRA:

$$\text{TRA} = \frac{\text{TC} - \text{TA}}{Q_{\text{radiated}} + Q_{\text{convected}}} = \frac{90 - 40}{5.937 + 20.964} = 1.859 \text{°C kft / kW} \tag{32}$$

The time constant of the first-order thermal model is provided then as

$$\begin{aligned} \text{Thermal Time Constant} &= \text{THC} \bullet \text{TRA} \\ &= 392.086 \bullet 1.859 = 728.9 \text{ s} = 12.15 \text{ mn} \end{aligned} \tag{33}$$

The practical meaning of this time constant is that if a step current is applied to the conductor, it will take 12.15 minutes for the conductor to reach 63 percent of the new steady-state temperature value.

Final Settings

Let us assume the line is located in the Montreal (Canada) area. Assume the routine is started with the line open in summer time. We get the final set of settings that has to be introduced into the routine as constants.

Table 14 Final Settings

Setting	Definition	Value
DSH	default solar heating	0
SAC	solar absorption coefficient	0.5
DIA	conductor diameter	1.108
LSTD	longitude of time standard	75.00
LON	longitude of conductor	73.43
LAT	latitude of conductor	45.56
R_{ac}	AC resistance at 25°C	0.022159
R_{delt}	temperature coefficient of AC resistance	0.0000833
THC	thermal heat capacity	392.086
TRA	thermal resistance to ambient	1.859
EAT	estimated ambient temperature	0
EOT	estimated offset temperature	0
TH	high temperature threshold	90
TL	low temperature threshold	80
TI	conductor initial temperature	25
THE	thermal trip enable	1
TSE	thermal sensor enable	1
SGE	solar generator enable	1

The thermal model implemented for this example is shown in Figure 3. PCT10 and PCT11 are two conditioning timers with both a pickup and a dropout time of 10 cycles.

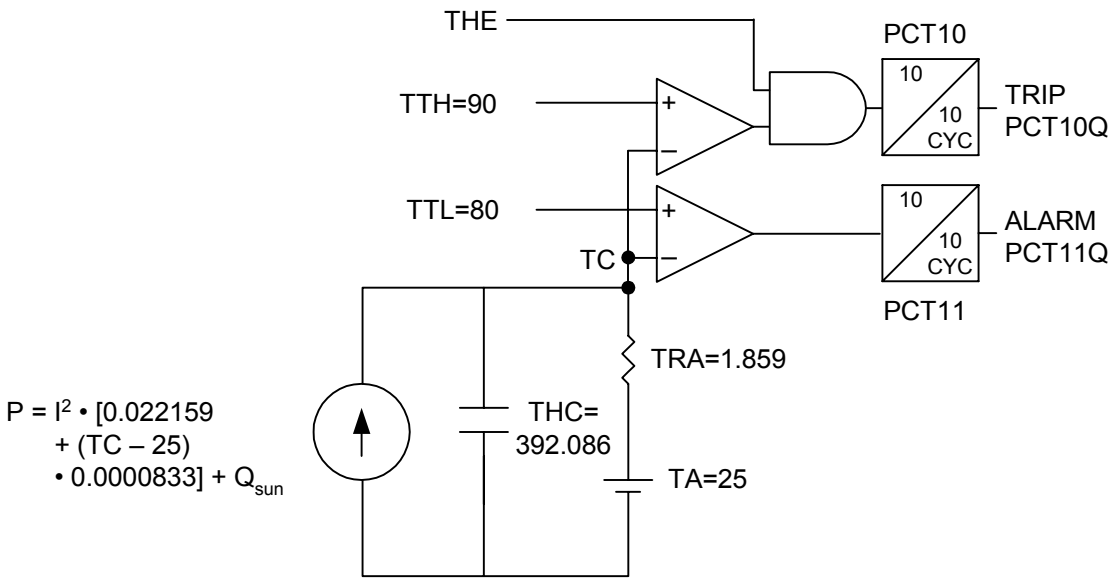

Figure 3 Example of Thermal Protection

TRANSMISSION LINE RELAY PROGRAMMING CAPABILITIES

The transmission line relay on which the line thermal protection element is implemented has user-friendly programming capabilities consisting of mathematical and logical equations using a language similar to BASIC. It is beyond the scope of this paper to describe the complete range of programming capabilities, but the following features have been used for the purpose of implementing the line thermal algorithm:

1. Sixty-four floating-point mathematical variables noted PMV01–PMV64 are available for the purpose of equation evaluation or memory storage. The four basic algebraic operations (addition, subtraction, multiplication, and division) are applicable on these variables together with the algebraic functions abs (absolute value of), sin, cos, sqrt, log, acos, asin, and ln.

2. Sixty-four Boolean variables represented as PSV01–PSV64 are available. All basic Boolean operation as OR, AND, NOT are available. Comparisons (>, >, =, <=, >=, <>) are applicable to floating-point variables and their outputs are defined as Boolean variables.

3. Sixteen conditioning timers noted PCT01–PCT16 are used to condition Boolean values. PCT01IN represents the logic input, PCT01PU the pickup time in cycles, PCT01DO the dropout time in cycles, and PCT01Q the logical output.

4. Analog values of phase currents represented as LIARMS, LIBRMS, and LICRMS are available as 10-cycle averaged root-mean-squared (rms) quantities.

5. Analog real-time variables such as day-of-the-year, hour, and minutes are available and represented as DDOY, THR, and TMIN, respectively.

6. Analog values for temperature measurements are acquired by an external module and noted RTD01–RTD12. Twelve RTDs can be attached to the module that transmits to the line relay at the rate of two sets of measurements per second by way of an optical fiber (see Figure 4).

Temperature measurements are represented as RTD01–RTD12. For the purpose of this application, RTD01 is the ambient temperature measurement.

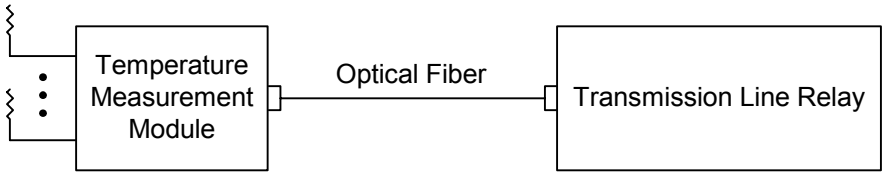

Figure 4 Ambient Temperature Measurement Principle

PROGRAM FLOW CHART

The simplified program flow chart is shown in Figure 5.

1. The first time the routine is processed (detected by PFRTEX = 1), the initial conductor temperature is entered.
2. If the setting SGE = 1, the heat power from the sun is computed; otherwise, it is set to the value DSH.
3. The maximum of the three-phase currents is then chosen as the conductor current.
4. The temperature increment is then computed by implementing Equation (6). The conductor temperature is then integrated with an integration step equal to 1/8 of a cycle or 0.0020833 s at a nominal frequency of 60 Hz. This integration step corresponds to the routine internal processing rate.
5. The routine then simply verifies if the computed temperature is above the alarm threshold or the tripping threshold. Before tripping or triggering an alarm, the signals are processed through two conditioning timers with a pickup and a dropout time of 10 cycles.

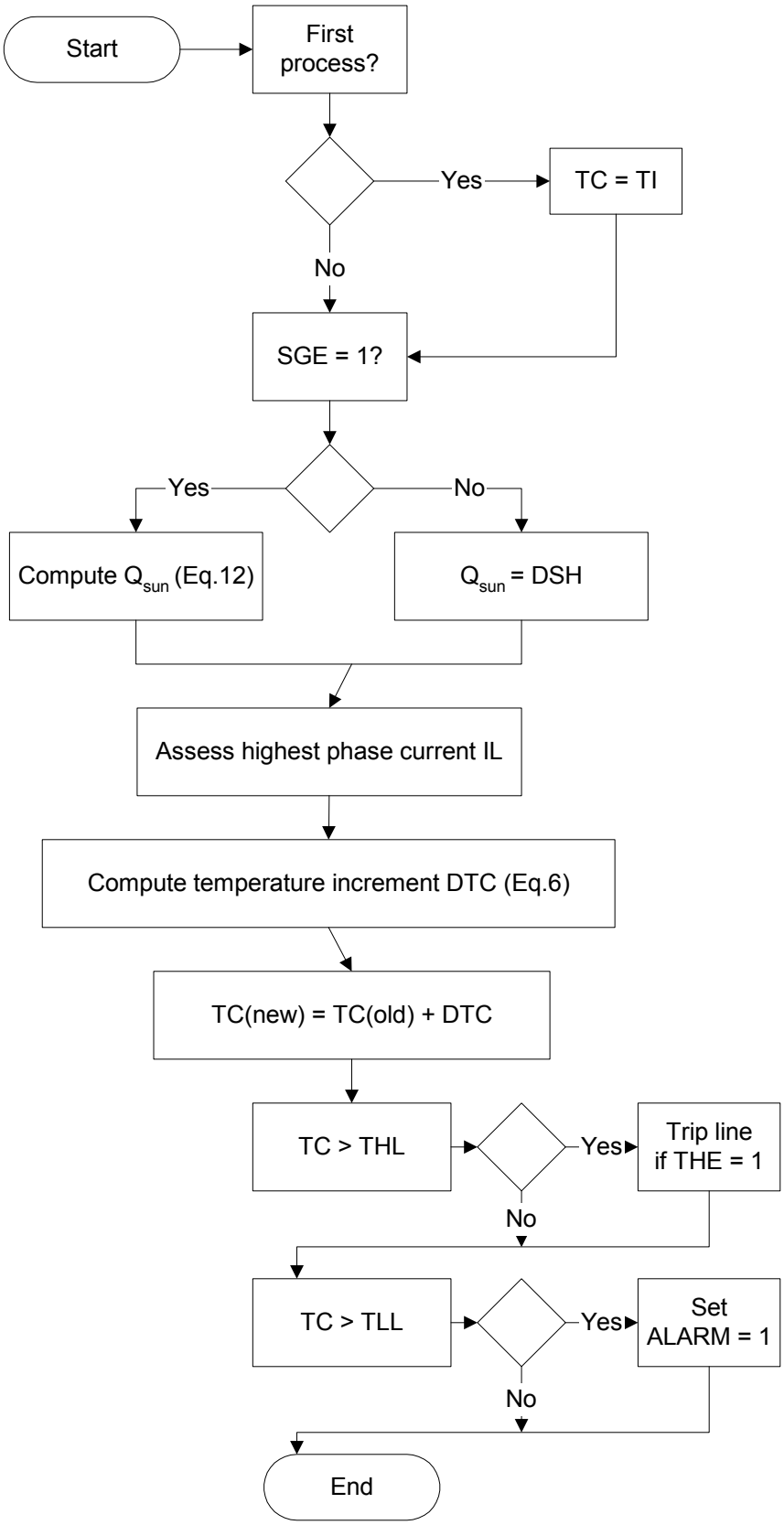

Figure 5 Simplified Line Thermal Model Flow Chart

PROGRAM IMPLEMENTATION

An example of the routine coding as it would be implemented by a user is shown in Figure 6 and Figure 7. Note that power measurements are made in kW and that temperature measurements are in degrees Celsius.

1. Lines 1–19 introduce all the line thermal element settings.
2. Lines 20–39 implement the computation of Q_{sun} or the heat power from the sun following Equation (12) through Equation (17). Note that Q_{sun} has to be positive (daytime) or zero (nighttime).
3. Lines 40–42 introduce the conductor initial temperature value.
4. Lines 43–46 perform the maximum phase current determination.
5. Lines 47–48 establish the ambient temperature depending on if we use a set value or a temperature measurement.
6. Lines 49–52 establish the conductor temperature by implementing Equation (6) and Equation (7).
7. Lines 53–55 determine the alarm output.
8. Lines 55–58 determine the trip output.

```
1     PMV03 := 70.430000                                  #CONDUCTOR LONGITUDE
2     PMV04 := 75.000000                                  #LSTD
3     PMV05 := 0.500000                                   #SAC
4     PMV06 := 0                                          #VALUE OF DEFAULT SOLAR HEATING
5     PMV07 := 0                                          #ESTIMATED OFFSET TEMPERATURE
6     PMV08 := 1.000000                                   #DIAMETER
7     PMV09 := 45.560000                                  #CONDUCTOR LATITUDE
8     PMV10 := 25                                         #VALUE OF INITIAL TEMPERATURE
9     PMV11 := 0.02216                                    #VALUE OF RAC CONDUCTOR RESISTANCE
10    PMV12 := 0.00008333                                 #VALUE OF RDELT TEMPERATURE COEFFICIENT
11    PMV13 := 392.086                                    #VALUE OF THC THERMAL HEAT CAPACITY
12    PMV14 := 1.859                                      #VALUE OF TRA THERMAL RESISTANCE TO AMBIENT
13    PMV15 := 90                                         #VALUE OF TH HIGH TEMPERATURE THRESHOLD
14    PMV16 := 80                                         #VALUE OF TL  LOW TEMPERATURE THRESHOLD
15    PMV17 := 0                                          #ESTIMATED AMBIENT TEMPERATURE
16    PMV18 := RTD01                                      #VALUE OF A TA AMBIENT TEMPERATURE
17    PSV05 := 1                                          #STATE OF SGE SOLAR GENERATOR ENABLE
18    PSV06 := 1                                          #STATE OF THERMAL SENSOR ENABLE
19    PSV18 := 1                                          #STATE OF THERMAL TRIP ENABLE
20    PMV01 := DDOY                                       #DAY OF THE YEAR
21    PMV02 := THR + TMIN * 0.0166667                     #HOURS OF THE DAY
22    PMV20 := 23.450001 * SIN((284.000000 + PMV01) * 0.98630137)                  #SUN DECLINATION
23    PMV21 := (PMV02 - 12.000000) * (-15.000000)                                  #LOCT
24    PMV22 := PMV21 + (PMV03 - PMV04)                                             #WS
25    PMV24 := SIN(PMV20) * SIN(PMV09) + COS(PMV20) * COS(PMV09) * COS(PMV22)      #COS(Z)
26    PMV25 := PMV24 * PMV24
27    PMV27 := 27682.000000 * PMV24 - 297.000000 - 44416 * PMV25
28    PMV25 := PMV24 * PMV25
29    PMV27 := PMV27 + 40023 * PMV25
30    PMV25 := PMV25 * PMV24
31    PMV27 := PMV27 - 17469 * PMV25
32    PMV25 := PMV25 * PMV24
33    PMV27 := PMV27 + 2498 * PMV25
                                    (continued on next page)
```

```
                                    (continued from previous page)

34    PMV28 := PMV27                                          #SIR VALUE
35    PMV29 := PMV05 * PMV08 * PMV28                          #QSUN VALUE
36    PSV01 := PMV29 >= 0
37    PMV30 := (PMV29 * 0.001) * PSV01
38    PSV08 := NOT PSV05
39    PMV30 := ((PMV29 * 0.001) * PSV01) * PSV05 + PMV06 * PSV08          #QSUN VALUE
```

Figure 6 Routine Coding: Introduction of Settings and Computation of Q_{sun}

```
40    PSV02 := PFRTEX                                         #DETECTION OF FIRST PROCESING INTERVAL
41    PSV03 := NOT PFRTEX
42    PMV35 := PMV10 * PSV02 + PMV35 * PSV03                  #INTRODUCTION OF THE TC INITIAL VALUE
43    PSV10 := (LIARMS >= LIBRMS)AND (LIARMS >= LICRMS)       #STATE OF PHASE A LARGEST CURRENT
44    PSV11 := ((LIBRMS >= LIARMS)AND (LIBRMS > LICRMS)) OR ((LIBRMS > LIARMS) AND (LIBRMS >= LICRMS))
45    PSV12 := ((LICRMS >= LIARMS)AND (LICRMS > LIBRMS)) OR ((LICRMS > LIARMS) AND (LICRMS >= LIBRMS))
46    PMV19 := LIARMS * PSV10 + LIBRMS * PSV11 + LICRMS * PSV12 #CHOICE OF GREATEST RMS PHASE CURRENT
47    PSV07 := NOT PSV06
48    PMV32 := (PMV18 * PSV06 + PMV17 * PSV07) + PMV07        #VALUE OF AMBIENT TEMPERATURE
49    PMV36 := ((PMV19 * PMV19) * (PMV11 + (PMV35 - 25) * PMV12)) * 0.001
50    PMV37 := ((PMV36 + PMV30) / PMV13) - ((PMV35 - PMV32) / (PMV13 * PMV14))
51    PMV38 := PMV37 * (0.00208333)                           #TEMPERATURE INCREMENT
52    PMV35 := PMV35 + PMV38                                  #TEMPERATURE INTEGRATION
53    PCT10IN := PMV35 > PMV16                                #DETECTION OF ALARM STATE
54    PCT10PU := 10
55    PCT10DO := 10
56    PCT11IN := (PMV35 > PMV15) AND PSV18                    #DETECTION OF TRIP STATE
57    PCT11PU := 10
58    PCT11DO := 10
```

Figure 7 Routine Coding: Computation of Conductor Temperature and Element Outputs

Figure 8 shows the measured conductor temperature rise when subjected to a primary current step of 791 A over an interval of time of 30 mn. The temperature decay occurs when the current step is removed. For this experiment, Q_{sun} has been set to zero, TA has been set to a fixed value of 23°C, and the thermal time constant is set to 5 mn (TRA = 1.859 and THC = 161.38). The maximum temperature reached is 51.09°C when the theoretical value as provided by Equation (10) is 51.33°C.

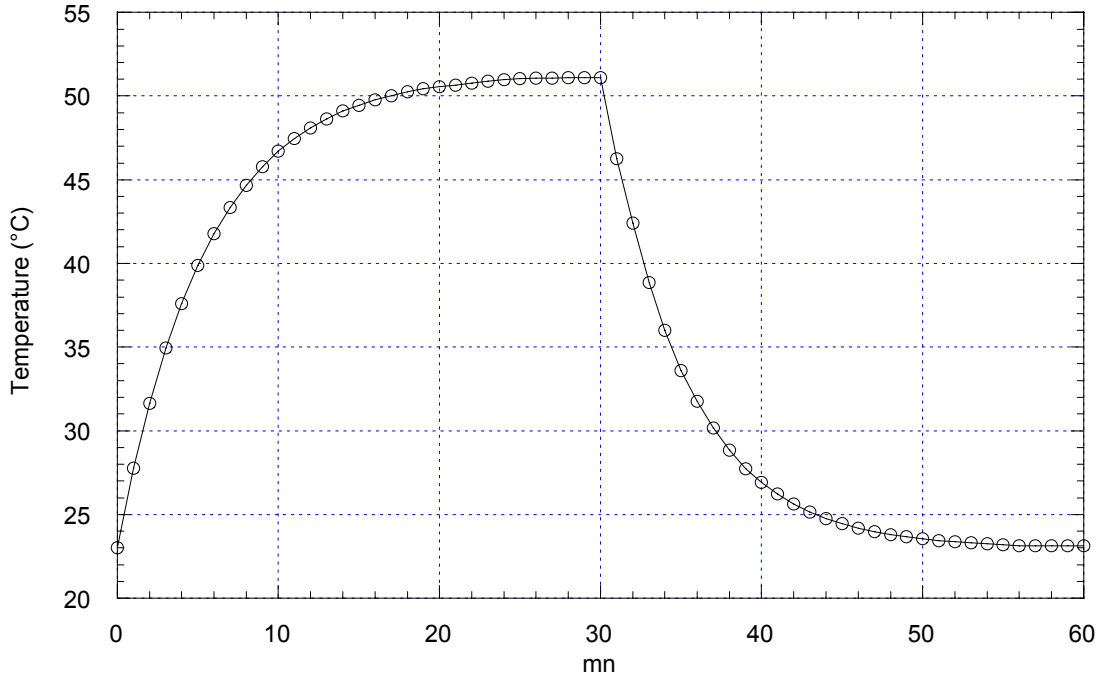

Figure 8 Conductor Temperature Rise and Decay

CONCLUSIONS

In this paper, it has been shown that a reliable line thermal protection element can be implemented by assuming the conditions of a worst-case scenario: the line temperature is computed on the line section assumed to have the greatest external ambient temperature and exposed to the maximum solar heating.

The element can be implemented into a transmission line relay with programmable mathematical and logical equation capabilities. Necessary analog quantities are phase currents, real-time variables like day-of-the-year, hours, and minutes, and finally an external measurement of the ambient temperature.

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BIOGRAPHIES

Gabriel Benmouyal, P.E., received his B.A.Sc. in Electrical Engineering and his M.A.Sc. in Control Engineering from Ecole Polytechnique, Université de Montréal, Canada in 1968 and 1970, respectively. In 1969, he joined Hydro-Québec as an Instrumentation and Control Specialist. He worked on different projects in the field of substation control systems and dispatching centers. In 1978, he joined IREQ, where his main field of activity was the application of microprocessors and digital techniques to substation and generating-station control and protection systems. In 1997, he joined Schweitzer Engineering Laboratories in the position of Research Engineer. He is a registered professional engineer in the Province of Québec, is an IEEE Senior Member, and has served on the Power System Relaying Committee since May 1989. He is the author or co-author of several papers in the field of signal processing and power networks protection.

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