Development of an Underground Cable Temperature Calculation Program Using the Neher-McGrath Method

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Abstract—the method of calculating underground cable temperatures and ampacities has long existed. The calculation herein is done under prescribed conditions with de-rating factors applied to cater for real world conditions. This yields an approximated value for the resulting temperature of a distribution feeder cable.

The underground cable temperature calculation program developed handles this situation. It is PC and Macintosh compliant since it was developed using the JAVA programming language. The program can calculate the temperature of medium power voltage cable laid in PVC conduit within a ductbank. [The user may alter the standardized data for the cable design and installation method if necessary within the program]. The program calculates the temperature of cables from steady-state cyclic load current according to the specified coincidence load factor [or cyclic load factor] and data. Currently, it can handle power cables operating from 12kV to 33kV.

Index Terms—**Distribution Feeder, Temperature.**

I. Introduction

Southern California Edison [SCE] has over 12,000 miles of underground distribution feeder cables in their system. These cables leave substations through underground getaways constructed from cement and PVC conduit. When a high amount of 3 phase feeders exit the substation together at high ampacity values, the cables may heat up significantly. The cables are rated for a certain temperature and life span, when the temperatures exceed the nominal rating, the life span degrades which may eventually result in breakdowns or failure. At grossly high temperatures, there is the possibility of the underground cable melting due to high stress from heat transfer. It is therefore important for SCE to be aware of the ductbank configurations and loadings throughout the system and to be aware of possible thermal deterioration due to high loading. This involves complicated mathematical calculations and thus the need for ductbank cable temperature calculation application arises. Equations develop by Neher and McGrath are the foundation of calculating and monitoring the temperatures within the ductbank program.

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II. Calculation

THE basis for most high-voltage underground ampacity calculations worldwide is an international standard, IEC 287. IEC 287 covers medium-voltage and high voltage cables, many different constructions, and many installation types. The Neher-McGrath method based on NEC standards is used to calculate ampacities here in the U.S.

Both methods employ the application of thermal equivalents of Ohm's and Kirchoff's Laws to a simple thermal circuit. In this program, the method covered by Neher-McGrath is used.

When the conductor is energized, heat is generated within the cable. This heat is generated due to the I^2R losses of the conductor, the dielectric losses in the insulation and losses in the metallic component of the cable. The ampacity of the cable is dependent on the way this heat is transmitted to the cable surface and ultimately dissipated to the surrounding. As shown in figure 1, the cable materials and externalities represent a series circuit of thermal resistances. The thermal resistances control heat dissipation from the conductor.

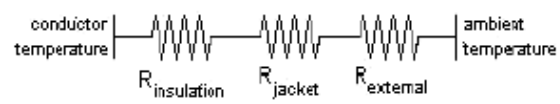

Figure 1- Thermal circuit model of a power cable.

Thus, the efficiency of heat dissipation is dependent upon the various thermal resistances of the cable material and the external backfill and soil plus the ambient temperature around the cable. If the cable is able to dissipate more heat, the cable can carry more current.

The normal maximum continuous rating of the cable is dependent on a number of factors. Of these the one that is most important is the maximum permissible conductor temperature. The maximum permissible current rating is the loading in amperes which, applied continuously until steady conditions are reached, will produce the maximum allowable conductor temperature. Steady state is reached when the rate of heat generation in the cable is exactly equal to the rate of heat dissipation from the surface of the cable. This steady state is the only condition considered when calculating the maximum permissible continuous current rating or temperature.

By applying the theory of heat transfer to the circuit shown in figure 1, equation (1) is obtained.

$$I = \sqrt{\frac{T_C - T_A}{R \times R_{CA}}} \qquad (1)$$

Where Tc is the temperature of the conductor,
Ta is the ambient temperature,
R is the electrical resistance in ohms,
Rca is the thermal resistance in thermal ohm feet.

Discovered by Joseph Fourier in the 1807, Equation No. 1 is sometimes called the Fourier heat transfer equation. Equation (2), as seen below, called the Neher-McGrath equation, is a more complex version of the Fourier heat transfer equation. The Neher-McGrath equation was discovered by two cable engineers in 1957. In the Neher-McGrath (NM) equation, Delta TD, is a term added to the ambient temperature, TA, to compensate for heat generated in the jacket and insulation for higher voltages. Delta TD is called the dielectric loss temperature rise and is insignificant for voltages below 2000V. Another term in the NM equation, (1+YC), is a multiplier used to convert direct current resistance (RDC) to alternating current resistance or impedance.

$$I = \sqrt{\frac{T_C - (T_A + \Delta T_D)}{R_{DC}(1+Y_C) \times R_{CA}}} \qquad (2)$$

Where $R_{CA}=R_i+R_j+R_e$ and:
Ta = Ambient temperature (°C)
Tc = Conductor Temperature(°C)
ΔTd = Temp. Rise due to dielectric losses (°C).
1+Yc = Skin & proximity effect
R_i = Insulation thermal resistance (TOF)
R_j = Jacket thermal resistance (TOF)
R_e = External resistance (Air, duct bank, etc).

The program uses this formula for calculating conductor temperature from a continuous current value. The other parameters of the formula are separately calculated and are dependant on the various other factors like cable construction types, installation types, and installation environment.

III. Cyclic Loading

As very often happens in Southern California, the loads are cyclic rather than continuous. Many cables take a longer time for the temperature to build up the equilibrium condition on which the continuous ratings are based on. In cyclic operation, a cable can carry a significantly heavier load for a given maximum conductor temperature than during constant load because the cable, and sometimes its environment, is capable of storing heat during periods of peak load and dissipating this stored heat when the load diminishes. Many factors have to be taken into account in calculating the temperature based on cyclic loading.

A. Important parameters affecting temperature

1) Load factor

The load factor is defined as the ratio of average load to peak load. The program uses 75% load factor as its default value. SCE's DDS uses 60% load factor.

2) Ambient Temperature

Ambient temperature defined in the program is 25 degrees Celsius, yet real-time conditions may prove otherwise. Please note that for underground duct banks, if the ductbank is already warm, it absorbs less heat and consequently the temperature may be increased during durations of high loading.

3) Conditions of Installation

The standardized installation type of underground distribution feeder systems is through concrete duct banks, not direct buried. The following should be noted.

a) A direct buried cable dissipates heat more readily than a cable in a duct.

b) Adjacent cables contribute heat and may induce additional losses in the cable itself. The addition of feeders in a ductbank increases the temperature for each of them.

4) Shielded grounding

Multipoint grounding increases circulating currents in the sheath. Therefore the losses will be increased and the rating will be decreased. Single-point grounding eliminates sheath currents, but induced voltages on the sheath have to remain within given limits even away from the grounded point. SCE typically uses multipoint grounding.

5) Cable Design

The cable design determines the ability to transfer heat from the conductors to the outer surface. This varies with the materials used and the number of layers in the construction. All parameters have been obtained from SCE's cable engineer for various types of cable. Currently, jacketed cable has not been added to the library.

IV. Power Cable Losses

A power cable consists of several components. The conductor and the insulation are the most basic components seen in any power cable. As the voltage increases other components are added to handle higher electrical stresses.

Figure 2 illustrates a cross section of a power cable which consists of a bedding, metallic sheath, steel wire armour and an outer jacket.

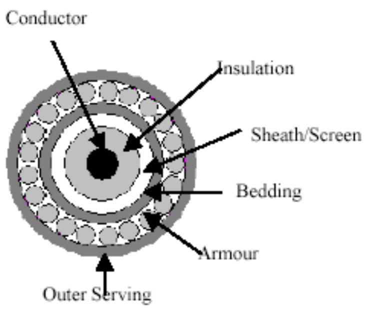

Figure 2 - Cross section of a single core metal sheathed, wire armoured power cable.

Nearly every part of a cable produces heat in one way or another. Within the external periphery of the cable there are four heat sources produced by losses in the following.

A. Cable Conductor
B. Metallic Sheath/Screen
C. Cable Armouring
D. Dielectric

A. Conductor I^2R Loss

A loss occurs in the cable conductor, which is proportional to the conductor resistance and to the square of the current being carried and it is known as "I^2R loss". This loss normally represents the largest heat source in the cable.

When the cable carries a.c. currents, the conductor resistance increases due to the skin and proximity effects. Skin effect is a phenomenon, which accounts for the increase in resistance of a conductor due to self inductance. This effect causes the current density in the conductor to be higher towards the outer surface. Although skin effect is generally considered negligible at power frequency, the effect becomes significant with larger cross sections (greater than 150 mm^2).

Proximity effect is a phenomenon of mutual inductance between the conductors of adjacent phases which creates the tendency for the currents in these conductors to flow along one side of the conductor cross section. This effect can be disregarded for cables smaller than about 185mm^2 cross section.

B. Sheath/Screen Losses

The magnetic fields of the currents flowing in the conductors induce E.M.F.'s in the metallic sheath/screen, which under certain conditions causes heavy currents to flow in the sheath/screen and generate losses.

There are two types of losses which occur as sheath eddy loss and the sheath circulating loss. Sheath eddy loss is due to the induced eddy currents, which flow circumferentially in the sheath/screen of the three-core cable or in the sheath/screen of the three single core cables. This loss reaches its maximum value when the cable conductors are situated as close as possible to one another. The loss can be reduced by increasing the sheath resistance and by increasing the ratio of cable spacing to sheath diameter. In many instances this loss is small and can be disregarded.

The sheath circulating loss, which only occurs in single core cables systems, is due to induced current flowing along metallic sheath/screen and returning through the sheaths of the other phase or through earth. This only exists when the sheaths of two or three single core cables are bonded together at two different positions, such as the ends of the cable route. This loss decreases as the sheath resistance is increased and the three cables are placed closer together. However, the closer formation results in a greater eddy loss and also increases the mutual heating of the three cables.

C. Armour Loss

Armour losses usually consist of the following.

1) • Losses due to currents in the armouring, both in the form of circulating currents and eddy currents.

2) • Losses due to magnetic field around the cable conductor under consideration and also losses due to the fields caused by currents in other conductors of a group of single core cables. These combined magnetic fields produce significant hysterisis losses. For power cables with non-magnetic armour, the usual practice is to take the combined sheath and armouring resistance as a whole and to calculate all losses as sheath losses.

D. Dielectric Loss

1) The dielectric losses of a.c. cables are proportional to capacitance, the frequency, the phase voltage and loss factor. The loss component of the loss factor (or the power factor) is made up of the following.

2) • Leakage current flowing through the dielectric, which is independent of frequency.

3) • Dielectric hysterisis, which is caused by the interaction of alternating field with the molecules of the constitutants of the insulation and is only present with a.c. voltage application. This is by far the largest effect.

4) • Ionisation i.e. partial discharge in the dielectric. The power factor of the cable insulation is dependent on frequency, temperature and applied voltage. It is of a very low order for low and medium voltage cables but this value rises rapidly with higher voltages.

V. METHODOLOGY

The main procedure for calculating temperatures is dependant on several variables. Sets of equations have been developed according to these variables. The main algorithm (i.e. the procedure for obtaining the temperature of a power cable) is shown as a flow chart in figure 3.

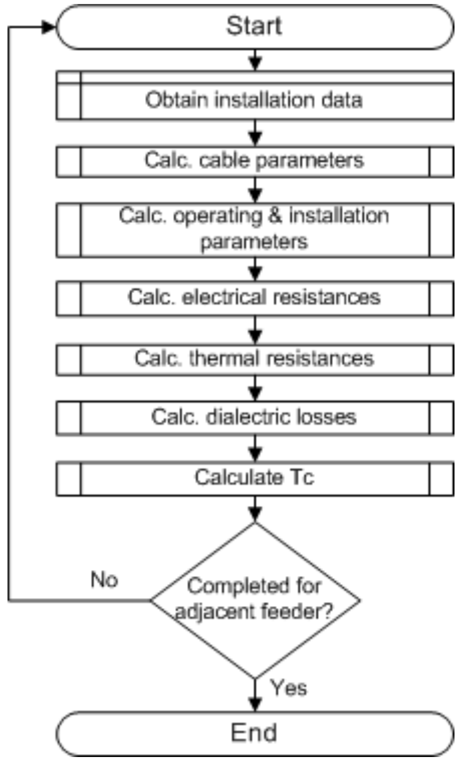

Figure 3. Process flow diagram for ductbank cable temperature calculation program.

A. Obtain installation data

B. Calculate Cable Parameters

C. Calculate Electrical. Resistance

D. Calculate Thermal resistances

E. Calculate Dielectric Loss

F. Temperature Calculation

The conductor temperature Tc is calculated by using equation 2 given in section 2. However, this equation is given in terms of Ampacity, and is therefore solved in terms of Tc with respect to I.

VI. THE SOFTWARE

A. An Overview

Users of Windows based software tools have become to expect a user-friendly graphical user interface for performing their tasks. Yet the software interface has been developed quite some time ago and needs to be redeveloped to provide the users with maximum efficiency and minimum complexity.

B. Factors to be taken into account in using the software

1) Ability to decipher field inventory maps
2) Access to circuit maps
3) Knowledge of ductbank configurations
4) Java runtime environment installed on client PC
5) Knowledge of complex data entry and parameter configuration
6) Awareness that real-time and simulated values can be obtained.

C. The Operation

The program consists of several dialog boxes which are used to navigate the user to the substation within SCE's given regions. Once there, the user can navigate or create structures that contain duct banks with distribution feeders running through them.

D. Calculation of Cable Temperature

Once all the needed data has been entered, the user can proceed to the DBLAST tab to view real-time values. Here, users can enter projected loading values for the distribution feeder layout to simulate the expected temperatures.

5.2.4 Reporting

Through the use of a relational database, reports have been created to systematically calculate temperatures for duct banks throughout SCE's system. They can be based off real-time values or projected loading.

VII. CONCLUSION

Simply stated the purpose of this project is to calculate temperature of a cable based on a set of user inputs. User inputs include, but are not limited to cable dimensions and materials, cable layout and cable operating conditions. This also permits quick and easy access to real-time loading of duct banks. In short this software is a valuable tool because it

• Automates time consuming process
• Handles many cable types and configurations
• Provide quick and accurate results
• Consolidates many calculations into one simple to use program
• Can be used as a tool in designing circuit additions

VIII. SUGGESTION FOR THE IMPROVEMENT OF THE SOFTWARE

• Obtain new jacketed cable parameters for the program.
• Re-design the graphical user interface for easier use.
• Include the ability to calculate current based on temperature.

IX. REFERENCES

Journals:

[1] Neher, J.H., McGrath, M.H., The Calculation of the Temperature Rise and Load Capability of Cable Systems, AIEE Transactions, volume 76, October 1957

[2] Powers W.F. The basics of power cables, www.southwire.com/tech/library, June 2001.

[3] Newton G.C. www.electrician.com/articles, January 2000.

X. Biography

Frank M. Gonzales received a B.S. degree in electrical and computer engineering with a minor in scientific computer programming from California State Polytechnic University, Pomona in 2002. He obtained a M.S. in electrical engineering from the University of Southern California in 2010. He is a registered Professional Engineer in the state of California. He is currently a Power System Planner at Southern California Edison in Pomona, CA.