A new approach for estimation of the dynamic thermal rating model parameters based on the IEC standard

Alireza **FARAHANI**, CYME Int. – EATON Corp., Montreal, Canada, alireza.farahani@eaton.com
George J. **ANDERS**, Lodz University of Technology, Lodz, Poland, george.anders@bell.net
Emmanuel **BIC**, General Cable, Montreau, France, EBic@generalcable-fr.com
Uwe **KEPPLER,** AP Sensing, Boeblingen, Germany, uwe.keppler@apsensing.com

ABSTRACT

Distributed Temperature Sensing, DTS, is a well-established technology that provides, in real time, temperature distribution all along the cable route. The technology is not fully exploited without real time thermal rating. In this paper, a new method based on the IEC standard to update the thermal model of cable installations in real time is introduced. The model has been tested on different types of installations. It is shown that one can use DTS readings, load variation and the IEC standards to calculate conductor temperature and optimize the usage of cable asset in steady state and transient situations.

KEYWORDS

distributed temperature sensing, real time thermal rating, dynamic feeder rating.

INTRODUCTION

In the majority of cable installations, maximum permissible conductor temperature is the parameter that limits current carrying capacity. This limiting temperature is determined by properties of the insulation material in direct contact with the conductor temperature conductor.

DTS systems provide, in real time, better understanding of how the conductor temperature responds to load variations. The current trend is to measure the temperature at a layer as close as possible to the cable conductor. To this end, fine steel tube with fiber optic sensor inside is included between concentric wires or set in direct contact with the jacket, duct or pipe depending on the type of cable and installation. In the case of existing installations, it is a common practice to install the fiber sensors in spare ducts close to the cables.

During the steady state operation, one can estimate the conductor temperature by using the load values, internal construction of the cable and the DTS readings for a given cable layer. The closer the fiber is to the cable conductor, the more accurate the estimate is. It is worth exploiting the full capacity of DTS systems once they are installed. The first step could involve using DTS systems to obtain conductor temperature. However, in practice the important question is how much more load can the cable system carry in the steady state, transient or emergency situations.

Parameters that affect the rating of a given installation are either constant or change with time. Geometry of the installation including depth and the relative position of the cables or cable construction are examples of constant parameters. For underground installations, soil thermal resistivity and ambient temperature are the most important parameters that depend on time. In the case of installations above ground, ambient temperature, solar radiation and wind velocity are important time varying parameters. Updating time varying parameters for cables in free air in real time can be very important because these installations usually have very low time constants.

External thermal resistance of a given cable is directly proportional to the soil thermal resistivity. It can contribute up to 70% of the conductor temperature rise above ambient [1]. Despite of its importance, its time variation or even steady state value are generally not known. Measurements at a given point along the cable route cannot provide a complete picture of its spatial variation. By the change in season and precipitation, soil thermal resistivity can change in time. Because the space/time variation of this important parameter is not known, normally a conservative approach is used and worst scenario is considered. The same conservative approach is used in the case of ambient temperature. Since the conductor resistance depends on temperature, knowing only the conductor current is not sufficient for obtaining accurate value of losses and the core temperature rise above ambient. However, if this is the only parameter that is measured, approximate calculations can still be performed with estimated soil ambient temperature as explained in [14]. The computed conductor temperature can be off by a few degrees in such case.

The brief discussion above should have clarified why one needs to use DTS systems together with the real time rating calculations. In a real time application, the time varying parameters of the thermal model are updated continuously in time. Using real time thermal model one does not need to use conservative approaches and the asset management is optimized. One can also make emergency or contingency plans more accurately taking into account the real operating point of the installation.

There are different approaches to update time varying parameters in real time. All these approaches use load variation and DTS readings. The criteria to use one approach over another could be the calculation time, accuracy, type of installation and, of course the cost. Ignoring the cost, the next section reviews the existing methods. The following section introduces a new method for estimating soil parameters. Next, the experimental setup and the results of the tests are presented. The last section contains the concluding remarks.

EXISTING APPROACHES

The objective in this section is to review published RTTR approaches that are validated within their defined set of assumptions and limits. It is not meant to compare different methods or comment on their shortcomings or relative advantages but rather to review the state-of-the-art in this field. The focus focuses on the underground installations.

Anders et al. [2] assumed the ambient temperature is measured. The load variation and temperature measurements at the cable surface are used to estimate the soil thermal resistivity. The computational algorithm takes full advantage of the shape of the measured current, temperatures and model nonlinearity. This means that the state estimation is not performed at each measurement point (the measurements can be recorded every minute), but the Gear and Adams-Multon predictor-corrector integration algorithms (the time step and iteration order are automatically changed depending on signal variation and required accuracy) are used to obtain desired precision.

Li et al. [3] introduce the following functional

$$F = \sqrt{\frac{1}{\tau}\sum_{j=1}^{N}[\vartheta_{est}(j\Delta t, \rho_{soil}, \vartheta_{amb}) - \vartheta_{measured}(j\Delta t)]^2 \Delta t} \quad [1]$$

where τ is the time interval over which the load and temperature readings are recorded for every time step Δt and N is the number of divisions Δt in τ. ϑ_{est} is the estimated temperature for the point in contact with fibre sensor at time $j\Delta t$. It is a function of ρ_{soil} and ϑ_{amb}. For the right choice of the soil ambient and thermal resistivity the estimated temperature ϑ_{est} approaches to the measured value $\vartheta_{measured}$ for each $j\Delta t$ point in time. Therefore, the problem of finding the unknown parameters ρ_{soil} and ϑ_{amb} is solved by minimizing the functional F with respect to the two unknown time varying parameters $(\rho_{soil}, \vartheta_{amb})$. The finite element algorithm is used to calculate the temperature of the given layer in contact with the fibre.

Brakelmann et al. [4] extend the equivalent electrical ladder network of the thermal circuit for heat transfer up to the node that defines the ambient. The external soil is divided into sections with their own thermal capacitances C_i and thermal resistances T_i. It is stated that 7 sections are sufficient for accurate estimation of conductor temperature variation. Adding more sections increases the calculation time without significant change in accuracy. In this approach, the unknown time varying parameters are the thermal resistances and capacitances for each section. Once the equivalent electrical network is formed, any appropriate software to analyse electrical circuits can be used. To obtain unknown parameters C_i and T_i of the ladder network an evolutionary genetic algorithm is used. Although the exact form of the functional is not given, the objective is to obtain the unknown parameters that minimize the difference between the estimated layer temperature and measured values for each instance of time. To this end, a commercial program SPICEOPT, which is based on SPICE, is used. To avoid nonphysical values for the unknown parameters, a search interval is defined.

In a similar approach Sakata et al. [5] use genetic algorithms to estimate lumped elements of the TC sections that represent the external environment. It is reasoned that for short emergency ratings up to six hours a two loop network can represent accurately the behaviour of the external soil. Therefore, the genetic algorithm is used to update 4 unknowns in real time. The inputs are the load variation, measured temperature at a given layer using the fibre optic sensors and the measured ambient temperature. It is stated that conventional minimization to estimate unknown parameters cannot be used. This is because different sets of parameter values yield close minima. Therefore, a genetic approach is used. Other possible methods like extended Kalman filter or simulated annealing are also recommended.

In a semi-analytical-experimental approach, Olsen et al. have used analytical expressions relating soil thermal resistivity and its specific heat to the soil's moisture content [6]. Although the soil thermal resistivity as a function of moisture content for different soil types show similar behaviour, the true dependence for the given soil type at the installation location should be obtained using local measurements. Once the dependence of soil thermal resistivity and specific heat on moisture content is known, the minimization approach to update the thermal model reduces to that of estimating the moisture content as the only independent parameter. The ambient temperature is measured or at the best is calculated using other analytical or numerical methods. Like the approach used by Brakelmann and Sakata, the external soil is divided into thermal TC sections. However, more thermal sections are used. The internal part of cable is divided into 6 sections and the external part is divided into 100 sections. The other difference is that instead of lumped element parameters T_i and C_i, a single independent parameter, namely the moisture content is updated in real time. To avoid unrealistic estimations of moisture content, a limit on the rate of change of this parameter is imposed.

It should be clear now that transient calculations are the fundamental component of any RTTR method. The way the effect of the external environment is modelled largely determines the time varying parameters that should be updated. Existing RTTR approaches differ on the choice of time varying parameters and the way they are updated. The references [7]-[9] provide a review of the transient calculation algorithms.

PROPOSED METHOD

All methods discussed above have one characteristic in common; namely, by adjusting one or more time varying parameters they all try to minimize the difference between the measured and computed value of the cable layer temperature. The approach described in this paper uses the same principle, but unlike [2, 4-6], it considers the situations in which the ambient soil temperature is not measured. The proposed approach is similar to the one described in [3]. However, whereas the method described in [3] uses the finite element method to obtain cable layers temperatures, the approach proposed here focuses on the application of the IEC analytical method.

In contrast with the IEC standard, several methods described in the previous section, model the response of the external soil by a number of TC sections. Each section could represent a tubular shell of soil with its own thermal resistance and capacitance. The difference in these methods can be traced back to the number of sections, and the way thermal resistance T and capacitance C of each section depend on soil thermal resistivity and specific heat. In a RTTR approach, they might also differ in terms of what parameters are updated in real time.

In the IEC standard, the temperature rise of any cable layer is divided into two parts. The internal temperature rise is the temperature rise of the layer above cable surface. This is obtained by solving the ladder network extended up to the surface of cable. The external part is the temperature rise of the cable's surface above ambient. An analytic method based on Kennelly's approach and resulting exponential integrals are used to obtain the external response.

$$\Delta\theta_M = W_t \frac{\rho_{soil}}{4\pi}\left[-Ei\left(-\frac{r^2}{4\delta t}\right) + Ei\left(-\frac{r'^2}{4\delta t}\right)\right] \quad [2]$$

where

$\Delta\theta_M =$ Temperature rise of point M above ambient, K.
$W_t =$ Total loss generated inside the cable, W/m.
$\rho_{soil} =$ Soil thermal resistivity, K.m/W.
$\delta = 1/(\rho_{soil}c) =$ Diffusivity of the soil, m^2/s.
$c =$ Specific heat for soil, J/m^3.
$t =$ Time, s.
$r =$ Distance from the cable axis to point M, m.
$r' =$ Distance from mirror image of cable from air/ground interface to the point M, m.

When point M is on the cable surface and time t approaches infinity, the above equation transforms to

$$\Delta\theta_M = W_t T_4 \quad [3]$$

where the external thermal resistance of the cable is

$$T_4 = \frac{\rho_{soil}}{2\pi}\log\left(\frac{4L}{De}\right) \quad [4]$$

Here De is the cable diameter and L is the cable depth. Total temperature rise of a given layer above ambient is the sum of the two parts where the external part is scaled by the attainment factor $\alpha(t)$ [1].

$$\Delta\theta(t) = \Delta\theta_{int}(t) + \alpha(t)\Delta\theta_M(t) \quad [5]$$

The method introduced in this paper is fully compliant with the IEC standard. The thermal ladder network for the internal part of the cable is developed using the IEC standard 60853 [10]. Temperature evolution at the cable surface in response to a step load is given by equation (2). The IEC Standard 60287 is used to calculate the steady state parameters like the internal thermal resistances and heat losses [11]. In the method presented here, the unknown parameters are the soil thermal resistivity and ambient temperature. The effect of soil thermal capacitance is seen in the exponential integrals by the value assigned to the soil diffusivity. Diffusivity of the soil is inversely proportional to specific heat. One might decide to consider soil diffusivity as the third unknown parameter to be updated. However, this increases the calculation time in a real time application without adding much accuracy. One should note that when the thermal diffusivity is not known, the IEC standard recommends that the value equal to $0.5 \times 10^{-6} m^2/s$ should be used. This is followed by the method proposed here.

All existing RTTR solutions use at least load variation and DTS readings at a given cable layer as the input. There are two steps in obtaining solutions to the steady state or emergency questions defined by the user. In the first step, the unknown parameters that define the thermal model of installation in real time are updated. In the second step, the conductor temperature and the steady state or emergency ratings are calculated. Since in emergency rating calculations one is looking into the future based on present real time conditions, there is no choice but to assume that during the duration of the emergency the thermal parameters will not change significantly. Of course, one can monitor the response of the cable installation to the emergency load as time passes by to update any changed parameter and take necessary decisions.

In the method introduced in this paper, at each instant of time t the load variation and DTS readings for the past time interval τ are used to update the unknown soil thermal resistivity $\rho_{soil}(t)$ and ambient temperature $\theta_{amb}(t)$ at the present instant t. Depending on the time interval Δt between consecutive load or DTS readings, there are $N + 1$ stored measurements for either load or temperature at a given cable layer, $\tau = N\Delta t$. The load and DTS readings are synchronized. The length of the time interval τ depends on the time constant of the installation. The default is to use 24 hour window. This can be increased for deep installations with larger time constants or when more accuracy is needed. IEC standards for both steady state and transient calculations are then used to minimize the functional F in equation (1) for the best solution set $(\rho_{soil}, \theta_{amb})$. Once the unknown parameters are obtained, steady state rating is used to obtain maximum allowed ampacity based on real time thermal model of installation. This is one of the key objectives of the RTTR calculations. One does not need to use conservative approaches based in worst case scenarios and thus the usage of cable installation is optimized. Transient calculations are used to obtain conductor temperature at time t using the updated thermal model. As time and the 24 hours window moves forward in steps of Δt, the last data point from the input data buffer is omitted and a new data is added. The values for the unknown parameters for the past time t are used as the initial guess in the iterative approach used to update the new thermal parameters at time $t + \Delta t$. The next objective of the RTTR calculations is to look into the future for emergency or contingency plans. Once the unknown parameters and operating point for the present time are known, this is a straight forward application of transient calculations, assuming the load variation is known.

There is a lower limit on the time interval Δt. The limit depends on the length of cable route and the technology used to analyse the data to provide the temperature profile all along this route. All calculations needed to update the unknown parameters, do the steady state rating and calculate conductor temperature or emergency/contingency ratings, should not exceed time interval Δt. This is because one needs to deal with the new set of data, load variation and DTS readings, at the end of this time interval. Another practical barrier is that one might want to use one RTTR package to cover many different installations or different thermal sections of the same cable route. In this case, all calculations related to all thermal sections should be performed before the next set of measured data for a new point in time for all sections are available.

The discussion above clears the need for a fast and efficient method to update the unknown parameters. Updating the unknown parameters is the part that consumes most of the calculation time. In an iterative approach, choosing a good initial point reduces the calculation time significantly. In this case, the search interval is limited to a smaller domain close to the real solution. In the proposed method, the initial guess for soil thermal resistivity is the local standard value. The initial guess for soil ambient temperature can be obtained by a variety of means. It is recommended to extend at the joints or terminal points the same fibre sensors that are used to measure the cable layer temperature, far from the cables, to measure ambient. Practically it might not be possible to extend the fibres in normal direction to the cables up to at least $10m$ to make sure they are measuring the ambient temperature. However, with some error they can provide a good starting point. It is possible to define the search margin around soil thermal resistivity and ambient depending on how much accuracy is required and how much time is available to do all calculations. Although the general principle and approach are the same, depending on the installation type and the type of data available, one can adjust the input parameters. As an example, for tunnel installations one can use the readings of the fire detection alarms as an input parameter to initialize the value for ambient temperature. Another possible approach is to use Kusuda's formulae [12] to have an estimate of what the ambient temperature is. This is explained in the following.

One can assume that the temperature at air ground interface is periodic in time. Assuming further that the earth is homogeneous, the problem of heat conduction underground can be solved analytically to obtain the ambient temperature as a function of depth and soil thermal diffusivity [13]. The result is

$$\theta(y, t_h) = A + \sum_{n=1}^{\infty} \alpha_n e^{\left(-\sqrt{\frac{n\pi}{\delta t_{year}}}\right)y} \cos\left(\frac{2n\pi t_h}{t_{year}} - P_n\right) \qquad [6]$$

In which the phase delay P_n depends on the depth y

$$P_n = \beta_n + \sqrt{\frac{n\pi}{\delta t_{year}}}\, y \qquad [7]$$

t_h = Time in hours,
y = Positive depth relative to the air ground interface, m
t_{year} = Number of hours in the year, 8766 h,
α_n, β_n are related to the amplitude and phase of different harmonics of earth temperature at the interface. Origin of time can be for example first day of January.

In practice, higher harmonics can be ignored and the result above is simplified to:

$$\vartheta(y, t_h) = A + \alpha_1 e^{\left(-\sqrt{\frac{\pi}{\delta t_{year}}}\right)y} \cos\left(\frac{2\pi t_h}{t_{year}} - \beta_1 - \sqrt{\frac{\pi}{\delta t_{year}}}\, y\right) \qquad [8]$$

One can use equation (8) to obtain ambient temperature at any depth as long as the parameters $A, \alpha_1, \beta_1, \delta$ are known. It is shown that the annual average temperature at any depth A is close to annual average air temperature above ground. This can be found from the data by closest meteorological station. This temperature is also very close to Collin's well temperature for the installation location. Within a good approximation, the amplitude for temperature variation at air ground interface, α_1 is close to the amplitude of air yearly temperature cycle which again can be found using the meteorological data. Any small error is further reduced since the amplitude at a given depth decreases exponentially with depth. The recommended value for soil thermal diffusivity δ by IEC standard is used. The phase lag β_1 at the air ground interface is assumed to be close to the phase lag for air temperature cycle at the given location. The inaccuracy involved would be around a few degrees. One needs to remember that this is an approach to obtain a good initial guess for ambient temperature at a given depth. Equation (8) can serve the purpose for the underground installations.

TEST SETUP

During the prequalification test for one of the cable manufacturers performed on 2.500 mm^2 , enamelled Cu 420kV cables, the entire cable route had been equipped with 480m of compact external fiber-optic temperature sensor cable to monitor the temperature profile by a Raman OTDR based DTS instrument.

The sensor cable was a dielectric single gel-filled tube with 8 x 50/125 µm Multimode fibers, with a diameter of 6.5 mm and a weight of 35 kg/km.

The prequalification test was done according to the IEC 62067. The test arrangement covered 5 different installation conditions:

I. Cables installed in open air, **II.** Cables directly buried (0.8 m), **III.** Cables installed in a steel-plated shed above the ground, **IV.** Cables installed in a non-ventilated PE tube direct buried **V.** Cables installed in an underground concrete tunnel. Some of the installations are shown in Fig. 1.

Fig. 1 Four installations at which the RTTR system was tested

The test loop was heated by conductor current to a given temperature. The heating was applied for at least 15.5

hours. The conductor temperature was maintained within the stated temperature limits for at least 2 hours at the end of each heating period. This period has been followed by at least 32.5 hours of natural cooling. The total duration of one cycle was 48 hours.

100 cycles of heating and cooling have been carried out with a conductor temperature 0 to 5°C above the maximum conductor temperature in normal operation (90°C). 80 cycles of heating and cooling have been carried out with a conductor temperature of 105°C (emergency temperature). A voltage of 1.7 U_0 has been applied to the test loop during the whole test period (8760 hours).

To assess the ambient temperatures, which were used for the Real Time Thermal Rating (RTTR) calculations, loops of the sensor cable were deployed at various positions as shown in Fig. 2.

Fig. 2 Illustration of the ambient temperature measurement at various installations

The test setup involved also identical reference cables to the cables installed on the main loop of the test in an almost voltage-free setup, permitting to install thermocouples on the conductor as recommended in the standard. This is schematically shown in Fig. 3.

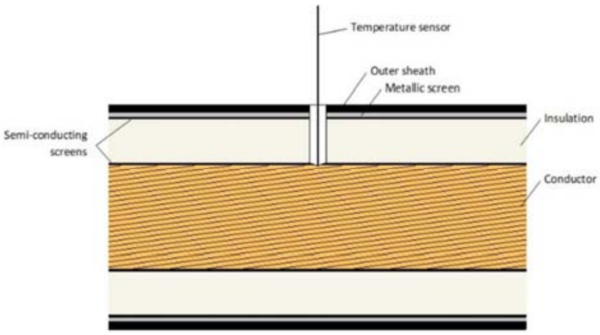

Fig. 3 Illustration of the location of the thermocouple probe on the cable conductor

These reference cables were installed close to the main loop to – be in the same thermal conditions. This made it possible to actually measure the conductor temperature for comparison with the RTTR results. The results for the section where the cable had been installed in a non-ventilated PE tube buried directly underground are shown below.

RESULTS OF THE RTTR CALCULATIONS FOR THE TEST INSTALLATION

DTS technologies permit evaluation of the entire temperature profile of the deployed test cable.

Figure 4 shows the temperature profiles of the cable test loop at different times from one outside cable termination to the far end termination, including the various installation conditions.

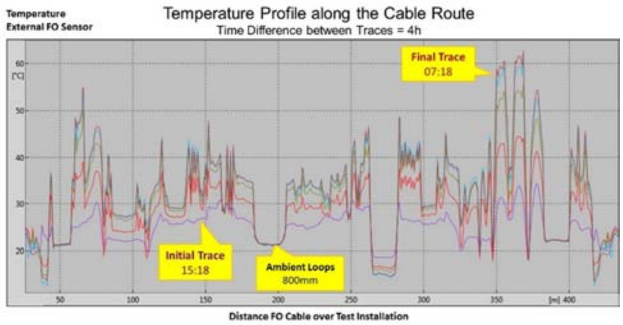

Fig. 4 Tmeperature profiles along the cable route

Figure 5 shows the ambient temperature during one heating cycle. The ambient temperature follows the seasonality – the ambient temperature inside the unventilated tunnel shows in addition a strong relation to each heating cycle.

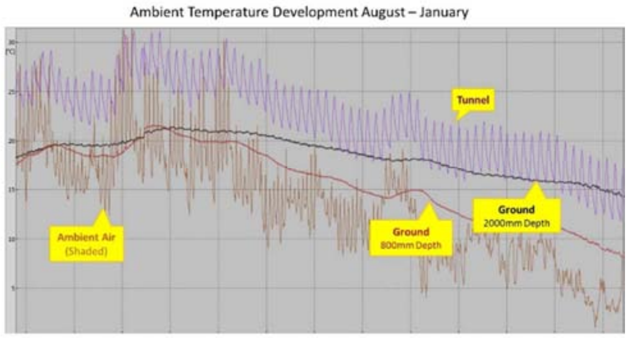

Fig. 5 Ambient temperature measured during heating cycles

From the available constants (cable type and laying condition) and the dynamic parameters (load, DTS readings, soil resistivity and ambient) the conductor temperature was calculated and is just slightly above the real – measured – value, as shown in Fig. 6.

CONCLUSIONS

The RTTR system presented here is characterized by a complex and accurate computational algorithm and has several important practical features. The system can be applied to all voltage levels, various cable constructions and installations, including: paper (high and low pressure fluid filled), extruded, gas, in air, directly buried, submarine, ducts and cables in tunnels. The minimum input to the calculations is the load current and cable (or pipe) surface or other layer temperatures obtained from fiber optic measurements. The program can compute not only steady-state and emergency ratings but also provide information on the time required to attain the specified temperature.

RTTR systems can be used to enhance the current-carrying capacity of power cables as well as to eliminate risks of overheating. They allow utilization of cable systems to their maximum capabilities and are particularly useful when a deferment of costly capital programs is desirable.

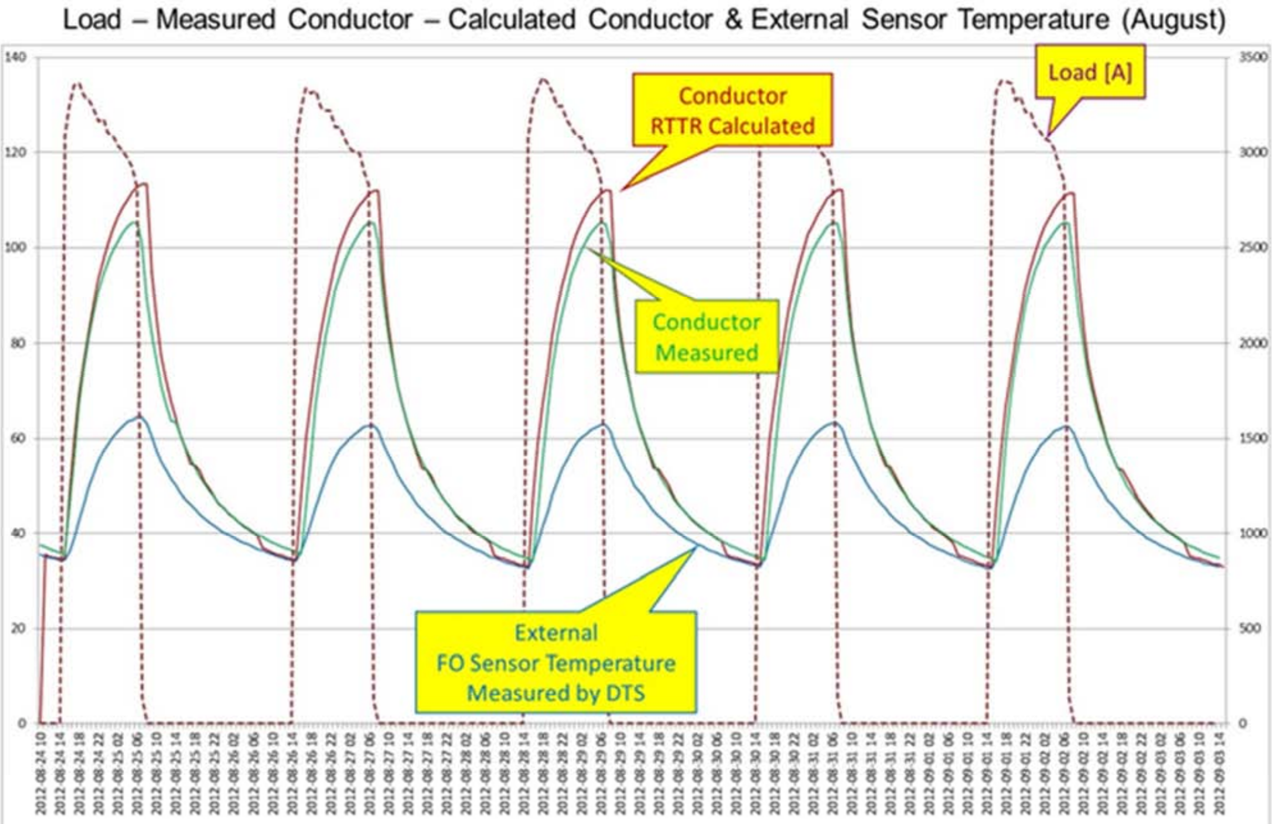

Fig. 6 Comparison of measured and computed conductor temperature for an underground installation

REFERENCES

[1] G.J. Anders, Rating of Electric Power Cables: Ampacity Computations for Transmission, Distribution, and Industrial Applications, IEEE Press / McGraw Hill, New York, 1997.

[2] G. J. Anders, A. Napieralski, M. Zubert and M. Orlikowski "Advanced Modeling Techniques for Dynamic Feeder Rating Systems", IEEE Transactions on Industry Applications, May/June 2003 Vol.39, No. 3, 619-626.

[3] H. J. Li, K. C. Tan and Qi Su, 2006, "Assessment of Underground Cable Ratings Based on Distributed Temperature Sensing ", IEEE Transactions on Power Delivery, vol. 21, No. 4, 1763-1769, Oct. 2006.

[4] H. Brakelmann, H. Hirsch, A. Rohrich, H. P. Scheiffarth and J. Stammen, 2007, "Adaptive Monitoring Program for Dynamic Thermal Rating of Power Cables", Proceedings of Jicable'07., Versailles, 2007.

[5] M. Sakata and S. Iwamoto, "Genetic algorithm based real-time rating for short-time thermal capacity of duct installed power cables", Proc. Intell. Syst. Appl. to Power Syst. Int. Conf., 1996, 85–90.

[6] R. Olsen, G. J. Anders, J. Holboell, and U. S. Gudmundsdóttir, "Modelling of dynamic transmission cable temperature considering soil specific heat, thermal resistivity and precipitation," IEEE Trans. Power Del., vol. 28, no. 3, pp. 1909–1917, Jul. 2013.

[7] Computer method for the calculation of the response of single-conductor temperature cables to a step function thermal transient, Electra 87, Cigre

[8] R. J. Millar, M. Lehtonen, "A Robust Framework for Cable Rating and Temperature Monitoring", IEEE Transactions on Power Delivery, January 2006 Vol.21, No. 1, 313-321.

[9] M. Diaz-Aguiló, F. de León, F., Jazebi, S., and Terracciano, M.," Ladder-Type Soil Model for Dynamic Thermal Rating of Underground Power Cables" PETSJ, Vol. 1, No. 1, 2014, 21-30.

[10] IEC, "Calculation of the cyclic and emergency current rating of cables", Int. Electrotech. Comm. Standard Series 60853, Jul. 1989.

[11] IEC Electric Cables—Calculation of the Current Rating—Current Rating Equations (100% Load Factor) and Calculation of Losses, Int. Electrotech. Comm. Standard Ser. 60287–1, Dec. 2006.

[12] T. Kusuda and P. R. Achenbach, Earth temperature and thermal diffusivity at selected stations in the united states Washington, DC, USA, Tech. Rep. NBS Rep. 8972, Jun. 1965, U.S. Dept. Commerce/Nat. Bureau Standards.

[13] H. S. Carslaw and J. C. Jaeger, "Conduction of Heat in Solids", Oxford at the Clarendon Press, 1959,. 81-83.

[14] G.J. Anders, Rating of Electric Power Cables in Unfavorable Thermal Environment, IEEE Press/John Wiley & Sons, New York, 2005.