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Accurate Determination of Ambient Temperature at Burial Depth for High Voltage Cable Ratings

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Abstract: **Recently installed high voltage cable circuits often contain temperature monitoring systems that measure the outer surface temperature of one phase of the circuit at discrete intervals over its entire length. This greatly assists in the calculation of the available cable rating. However, well established buried high voltage cable circuits very often have no additional temperature monitoring and the rating is determined using IEC287. In order to improve the accuracy of this rating calculation a model based on thermodynamic laws has been developed that determines the soil or backfill ambient temperature at the cable burial depth. This model uses weather data and can be used to calculate a predicted soil temperature for a given cable depth**

This paper will present the results obtained comparing ambient temperature measurements made at National Grid Transco's substation at Skelton Grange, Leeds, UK with predictions made using the ambient temperature model. The sensitivity of the model to input parameter sample rate and accuracy has been investigated. Results indicate that providing the meteorological data is sampled hourly and the weather station is no more than 25 miles distant, the ambient temperature can be predicted to within ±2°C.

INTRODUCTION

Transmission of electrical power using buried cables is limited by the temperature of the electrical insulation used for the cable [1]. Operating power cables above a specified maximum allowable temperature will cause the electrical insulation to age at an accelerated rate. The operating life of power cable insulation decreases exponentially with an increase in operating temperature [2, 3]. The temperature of an operating power cable is determined by the load being transmitted through the cable and the temperature of the ambient soil due to local climatic conditions. Using IEC287 the steady state rating (I) of a cable is defined as:

$$I = \left\{ \frac{\Delta\theta - W_d\left[\frac{1}{2}R_{TH1} + n_c\left(R_{TH2} + R_{TH3} + R_{TH4}\right)\right]}{rR_{TH1} + n_c r\left(1+\lambda_1\right)R_{TH2} + n_c r\left(1+\lambda_1+\lambda_2\right)\left(R_{TH3}+R_{TH4}\right)} \right\}^{\frac{1}{2}} \quad (1)$$

Where $\Delta\theta$ is the maximum permissible temperature rise for a cable having n_c cores each with an electrical resistance of r ohms per unit length. W_d is defined as the dielectric losses per unit length, λ_1 is the ratio of sheath loses to main conductor losses and λ_2 is the ratio of armour losses to main conductor losses. R_{TH1}, R_{TH2}, R_{TH3} and R_{TH4} are the thermal resistances across the dielectric, between the sheath and armour, between the armour and outside surface and between the outside surface and the ambient for a unit length of cable.

Cable ratings are also based on a number of variables including cable depth and local climatic conditions such as air temperature, wind speed and solar radiation and season. Based on these factors cables are given seasonal ratings, i.e. more load can be transmitted in winter when the ambient soil temperature is colder than during the summer months. However, these ratings tend to be conservative in their application so the cable rating is based on worst case parameters, so that even in the most extreme conditions the maximum operating temperature is not exceeded. These ratings in some cases are so conservative that the cable is operating at a level significantly under its potential.

Previous work [4, 5] has been carried out in this area in developing a model to simulate the effect of environmental parameters such as air temperature and solar radiation on the ambient soil temperature at cable burial depth. This work proved that a more dynamic ambient soil temperature prediction would result in a more reliable and accurate prediction of power cable capacity. The existing model assumes there are no additional sources of heat, and uses a simplified version of Poisson's equation:

$$Q_i = C_v \frac{\partial\theta}{\partial t} - \frac{1}{\rho}\frac{\partial^2\theta}{\partial d^2} \quad (2)$$

where θ is the temperature, C_v is the volumetric heat capacity, ρ is the thermal resistivity, d is the depth and Q_i is the internal heat generation. Assuming that there is no internal heat generation then (2) can be solved by modelling the soil as a series of n horizontal elements. The temperature of the kth element can be determined at every Δt seconds, such that after j time steps the temperature of the element is given by:

$$\theta_{j,k} = \theta_{j-1,k} + \frac{\Delta t}{C_k}\left\{\frac{\theta_{j-1,k-1}-\theta_{j-1,k}}{R_{k-1}} + \frac{\theta_{j-1,k+1}-\theta_{j-1,k}}{R_k}\right\} \quad (3)$$

where C_k is the thermal capacity of the kth element and R_k is the thermal resistance of the kth element. At a certain depth the soil remains at a constant temperature, Θ, known as the mean ground temperature, irrespective of weather conditions or the time of year. The depth of the nth element needs to be sufficient enough so that it can be assumed to be at Θ. Then the net heat exchange at the ground surface at the jth time step can be defined as:

$$q_{j,1} = q_{c_j} + q_{LW_j} + q_{sr_j} \quad (4)$$

Where q_c is the convective heat flux, q_{lw} is the longwave radiation heat balance and q_{sr} is the heating due to solar radiation at the ground surface.

The existing model was modified so that the effect of sample rates could be could be measured and dominant variables identified. The model was then used to predict the ambient soil temperature for one location using climatic data from several sites around the UK, in order to investigate the proximity of the meteorological station required for an accurate prediction to be made.

DETERMINATION OF AMBIENT SOIL TEMPERATURE AT CABLE BURIAL DEPTH

Meteorological data obtained for Leeds, UK, was used with the existing model to predict the ambient soil temperature and compared against known soil temperatures provided for a substation located at Skelton Grange, just outside of Leeds. The meteorological data was provided at half hour sample rates for air temperature, wind spend and solar radiation.

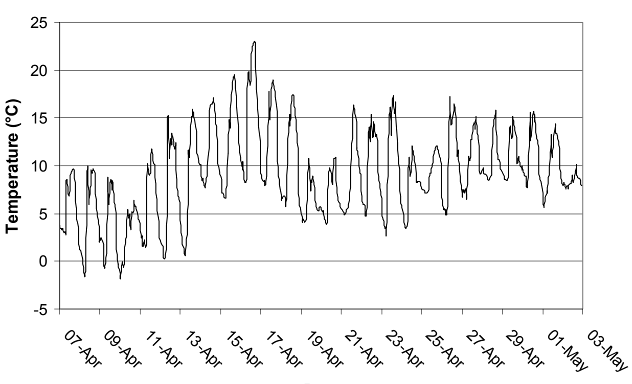

Figure 1 - Example of Temperature Data

To measure the accuracy of the model it was decided to use at least a month's worth of meteorological data and compare this to the known temperature over the same time period. April 2003 was chosen as the month that would be used. Figure 1 shows the air temperature data for Leeds during April 2003.

Dominant Meteorological Variables

The sample rate of each variable was varied in the model from every half hour to every six hours while keeping the sample rate of the other two variables constant at every half hour. The error between the actual recorded temperature and the predicted temperature was then calculated and hence the standard deviation for each case determined as shown in Figure 2.

From Figure 2 it can be seen that varying the sample rate of either the wind speed or solar radiation values does not significantly alter the accuracy of the model. However, if the sample rate of air temperature is taken above every 4 hours the accuracy decreases rapidly. Air temperature is the dominant input variable in predicting the soil temperature at cable burial depth.

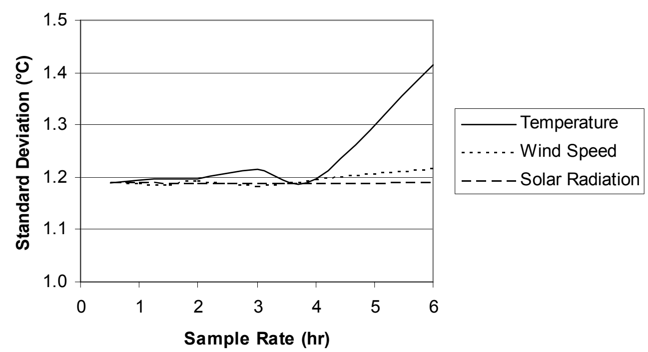

Figure 2 – Dominant Input Variable

Effect of Sample Rate

To further investigate the effect of variation of ambient soil temperature, the sample rate of wind speed and solar radiation were simultaneously sampled at rates varying between every half hour and every six hours. In each case the air temperature sample rate was varied over the same range. The standard deviation for each case was then determined, as shown in Figure 3.

Results indicate that the overall accuracy of the model is not compromised if the sample rate for air temperature, solar radiation and wind speed sample rate is at least every two hours. Based on these results all further simulations were completed using an hourly sample rate.

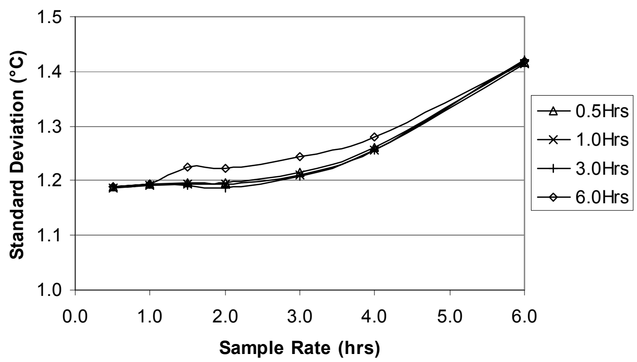

Figure 3 - Standard Deviation Against Sample Rate

Figure 4 shows the ambient soil predicted temperature for Leeds if an hourly sample rate is used for the input variables against actual measurements of soil temperature.

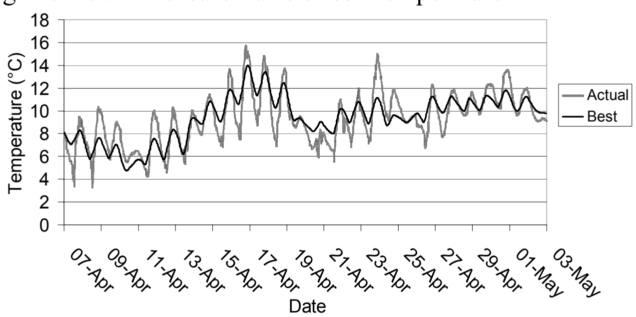

Figure 4 - Comparison of Actual Temperature to Best Case Predictions

Effect of Offset or Gain on Temperature

In an attempt to represent a distant measurement of ambient soil temperature two possible conditions were simulated: an offset to the air temperature; and a difference in diurnal variation of air temperature. An applied offset was varied from -5°C to +5°C in 1°C increments, and errors calculated for each case. Figure 5 shows the effect of an applied offset to air temperature on the accuracy of the model.

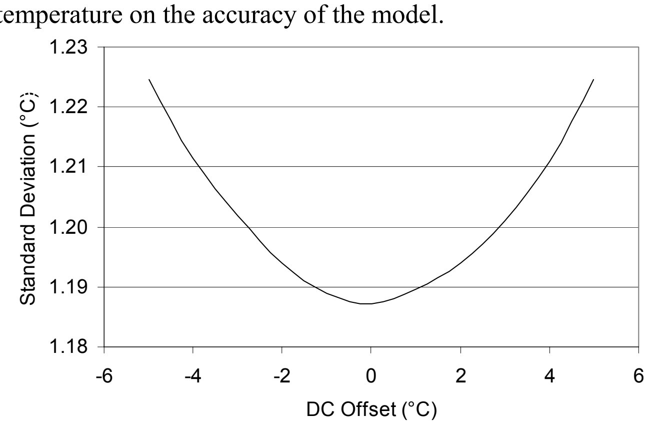

Figure 5 - Standard Deviation Against DC Offset

Results indicate that accuracy is effected if the measurement point is distant enough to have a greater than 3°K difference in air temperature.

To represent a different diurnal variation in air temperature the air temperature was scaled using a gain varying between 0.5 and 1.5 in 0.1 increments, and the errors calculated. Figure 6 shows the effect of this applied gain to the accuracy of the model.

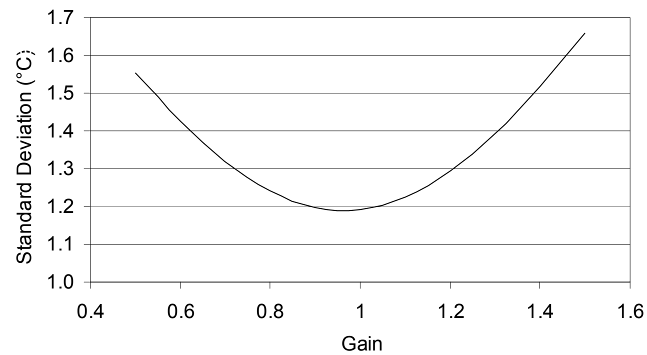

Figure 6 - Standard Deviation Against Gain

Results indicate that if the meteorological data is taken from a point distant enough to only have a diurnal variation of between 0.8 and 1.1 the accuracy of the model is not effected.

Effect of Using Remote Meteorological Data

Based on these simulations meteorological data for sites at various distances from Leeds were used to predict the ambient soil temperature at those locations and then compared to the measured temperatures for Leeds. The errors were then calculated to assess the accuracy of the model against the distance of the meteorological data from the site the temperature prediction is being made for.

Meteorological data for Sheffield (55km from Leeds), Manchester (72 km), Oxford (255 km), Southampton (350km) and Plymouth (480 km) was used to assess the accuracy of the model. Figure 7 shows the air temperatures at Sheffield and Plymouth, which were the nearest and furthest locations from Leeds.

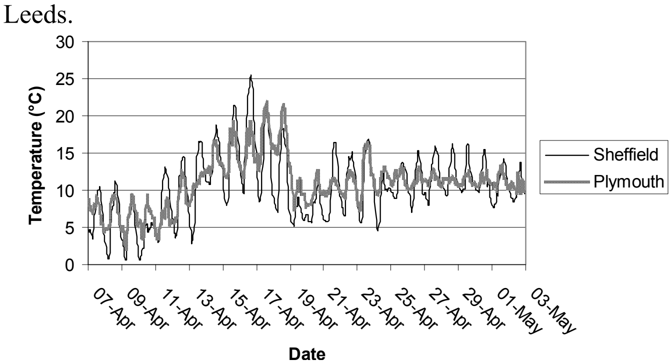

Figure 7 - Comparison of Nearest and Furthest Air Temperatures

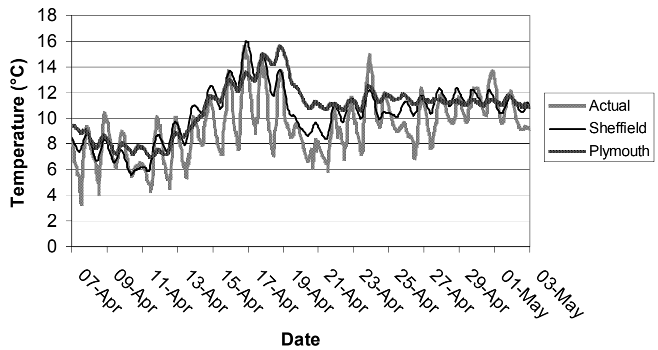

Figure 8 - Comparison of Predicted Temperatures

Figure 8 shows the predicted ambient soil temperatures for Sheffield and Plymouth.

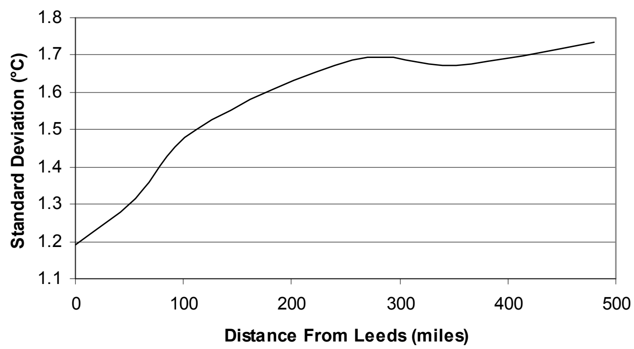

Figure 9 - Standard Deviation Against Distance

Using the value calculated when all meteorological variables are sampled at half hourly intervals, the standard deviation for each location was plotted against the distance from Leeds, as seen in Figure 9.

As would be expected the further the meteorological data obtained is away from the point where a prediction for the soil temperature is required, the greater the error. This indicates that ideally the meteorological site should be no more than 50km from the cable circuit.

CONCLUSIONS

A model using physical laws was derived and implemented into a computer program so that a prediction of ambient soil temperature can be readily made on an hourly basis using by inputting meteorological data. The results indicate that these predictions are significantly more accurate than the existing methods for rating the power capacity of buried electrical transmission cables.

It has been shown through experimentation with this model that the dominant effect on the estimate of temperature of a burial cable is the air temperature and that wind speed and solar radiation do not affect the cable temperature greatly. By optimising the sample rate necessary to make an accurate prediction of the ambient soil temperature, an estimation can be made to with 1°K of the actual temperature, while keeping the amount of meteorological data necessary to make the prediction to a minimum.

By using meteorological data from various sites around the UK to predict the ambient soil temperature and comparing the distance of these readings to a measured soil temperature, it can be estimated that in order to predict the soil temperature to within 1°K, the meteorological data must come from within a 50 km radius of the location of the cable. However, even is the meteorological data is taken from as far away as 300 miles a prediction of the ambient soil temperature can still be made to within 2°K.

ACKNOWLEDGEMENTS

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