Underground Power Cable Environment On-Line Monitoring & Analysis

J.S. Lyall Member, IEEE   G. Nourbakhsh   H.C. Zhao

Research Concentration in Electrical Energy
School of Electrical and Electronic Systems Engineering
Queensland University of Technology, Brisbane, Qld. Australia

Abstract: Knowledge of cable parameters has been well established but a better knowledge of the environment in which the cables are buried lags behind. Research in Queensland University of Technology has been aimed at obtaining and analysing actual daily field values of thermal resistivity and diffusivity of the soil around power cables. On-line monitoring systems have been developed and installed with a data logger system and buried spheres that use an improved technique to measure thermal resistivity and diffusivity over a short period. Results based on long term continuous field data are given. A probabilistic approach is developed to establish the correlation between the measured field thermal resistivity values and rainfall data from weather bureau records. This data from field studies can reduce the risk in cable rating decisions and provide a basis for reliable prediction of "hot spot" of an existing cable circuit.

Keywords: Thermal Resistivity, Cable Rating, Thermal Resistivity measurement, Monitoring, Probabilistic, Statistic

I. INTRODUCTION

Although soil thermal resistivity is the major parameter affecting the current rating of underground power cables it is also the least understood. It is very difficult to establish a good knowledge of the variations that occur over the life of the cable and usually this aspect is simply ignored. Route surveys and tests for the effects of variations of soil moisture may be carried for important circuits in order to establish a design value of the soil thermal resistivity. However in regions where long dry periods are not uncommon values in excess of three times those normally accepted are often encountered. Thus there is an obvious risk associated with such practices and failures have occurred. On the other hand there is also the risk of under-utilisation of an expensive resource with premature reinforcement of a circuit if thermal resistivity values are much lower than anticipated. Papers by Anders et al [1, 2]describe a method of constructing a model of the soil moisture variations based on a technique by Thornwaite[3]. From this a Monte Carlo simulation is used to construct a probability distribution of soil thermal resistivity variations. Also Blackwell et al[4] refer to the need for a statistical distribution for thermal resistivity for a probabilistic method of cable rating. Thermal resistivity is very sensitive to variations in soil moisture content, which in turn depends on rainfall and can vary on a daily basis. This paper describes a new technique for obtaining daily field values of thermal resistivity, illustrating the daily variations that can occur and how the data can be analysed to obtain probability distributions of thermal resistivity.

II. A NEW APPROACH

For daily measurement of soil thermal resistivity the only practical possibility is a permanent, automated site preferably with remote communications. Advances in computer and communications technology and consequent cost reductions have made this possible.

Fig. 1, is a diagrammatic representation of a measuring site with local experimental control, data storage and communications to a remote computer for downloading and analysis of the collected data. The automated test and data recording system (the "on-line monitoring system") contains the "transient spheres" located in backfill adjacent to the cable and in native soil, the data logger and heater control system for the spheres, a power supply, modems, telecommunications and finally a desk top computer. The on-line monitoring system can be remotely programmed to undertake various tests and locally record data at user specified intervals. Transient sphere tests are implemented every day at the same time, for the same duration. Data is stored at the remote site in random access memory and is unloaded to the laboratory for further processing as required. Multiple sites can be easily instrumented and tests routinely undertaken. No field trips are necessary other than maintenance. One of the sites under observation has now been in continuous operation for over 4 years, recording data consistently. The resulting data sets have provided a unique set of observations on the variability of both thermal resistivity and diffusivity.
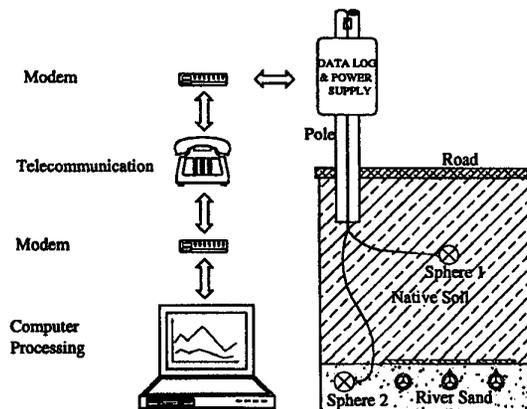

Fig. 1. Automated On-line Monitoring System

The transient sphere is a new technique for measuring the soil thermal parameters and consists of a spherical sensor for which an exact mathematical model can model the transient temperature rise. This enables the thermal resistivity and diffusivity to be determined. It also has the advantage of enabling robust construction for permanent burial.

Fig. 2, shows photograph of such sphere. It consists of a copper sphere approximately 100mm in diameter, which encloses a heating coil wound on a spherical former. Thermocouples are attached to the external surface and the sphere made watertight. Leads to the heater wires connected to a DC power supply or battery, which provides the heating current. Temperature rise is recorded as a function of time after a constant current is switched on.
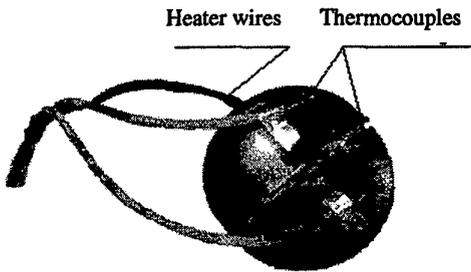
Heater wires   Thermocouples

Fig. 2. Photograph of transient sphere

The theory is based on the following equation of an infinite region bounded internally by a spherical surface, and for which the heat flux across the spherical surface is constant. The temperature rise on the surface of the sphere is given by the following formula [5]:

$$\Delta T = \frac{Wg}{4\pi r^2}\left(\sqrt{\frac{Dt}{\pi}}\left(1-e^{-\frac{r^2}{Dt}}\right)+r\cdot erfc(\frac{r}{\sqrt{Dt}})\right) \qquad (1)$$

Where:

g = Thermal Resistivity
D = Thermal diffusivity
W = Watts input
t = time
r = radius of sphere
$erfc(x) = (1 - erf(x))$

$$erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\,dt$$

Using the measured temperature rise curve the above equation can be solved to obtain the values of thermal resistivity and diffusivity. The technique is described in reference [6]

III. PROCESSING COLLECTED DATA

Data has been obtained from 3 sites (Edmonstone Street (since 1996) and Quay St no1 (1998) and 2 (1999)). An example of the collected and processed is shown in Fig. 3, to Fig. 5. The locations are three sites near the Brisbane central business district (CBD). Fig. 3, shows the derived values of thermal resistivity (TR (°C·m/W)) and diffusivity of a 110KV-cable route from June 1999 to Jan 2000. Fig. 4 shows the values of thermal resistivity at the same location in conjunction with rainfall from March to September 1998. Fig. 5, shows the values of thermal resistivity of backfill and native soil from an 11KV-cable route conjunction with rainfall from June to December 1999.
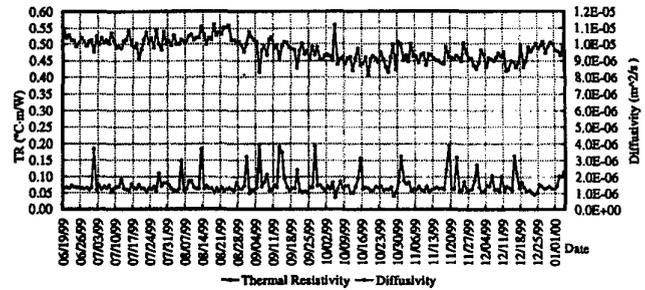
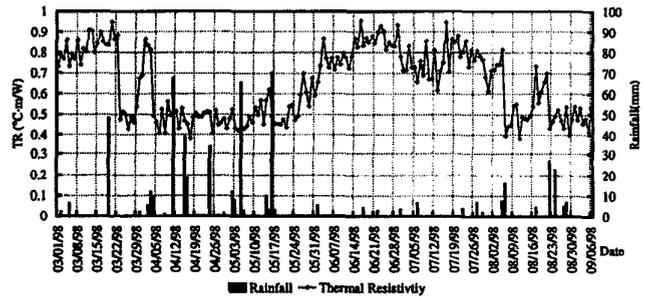Fig. 3. Soil Thermal Resistivity and Diffusivity - 110KV Cable

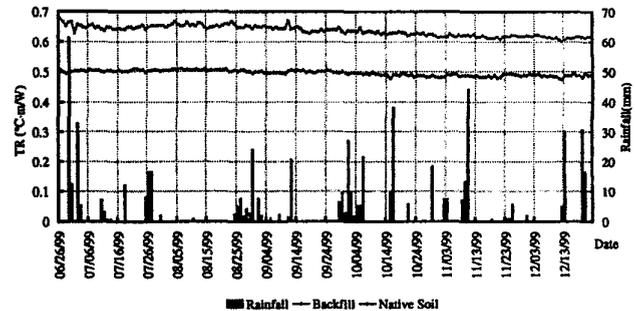Fig. 4 Soil Thermal Resistivity and Rainfall - 110KV Cable

Fig. 5: Rainfall and Thermal Resistivity of Native Soil and Backfill - 11KV Cable

IV. ANALYSIS OF DATA

For a given location it is clear that the soil moisture content is the most important factor in determining soil thermal resistivity and this in turn depends on the local rainfall. Thus rainfall can be closely correlated with an increased soil moisture content and consequently lower values of thermal resistivity. Conversely lack of rain will lead to an increase of TR. During the period from 1996 to 1998 in Brisbane, the precipitation and its seasonal variation followed a normal pattern, with periods of consistent wet weather during the summer months and long periods of low rainfall during the winter months. The variations in TR can be closely correlated with the rainfall as seen in Fig. 4. However, during late 1998 and 1999, the rainfall was unusual, with a consistent pattern of regular heavy rainfall with no periods less than two weeks without rain (Here "without rain" means average rainfall <= 2.5mm/week, and will use through out this paper). This kept the local soil saturated and hence the TR at a low, constant value as seen in Figures 3 and 5 that are two locations near the CBD.

The graphs in Fig. 3 to 5 illustrate some of the data collected over a period of four years and used to establish relationships between rainfall and TR. Thus Fig. 6 was obtained by accumulating the precipitation over a number of consecutive days and observing the changes in TR. The change in TR was only recorded if it had an initial value of 0.75 or greater (i.e. greater than 2 weeks without rain). The distributions show that even for modest amounts of rain a very significant reduction in TR can occur.
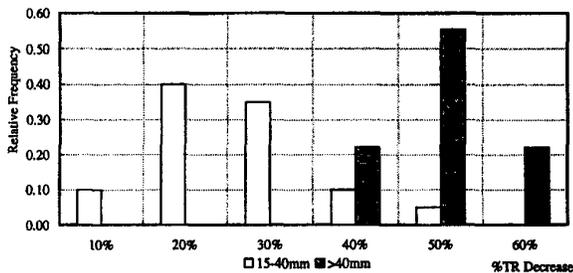

Figure 6. Probability of maximum changes in Thermal resistivity for 15-40mm and more than 40mm rainfall.

It was observed in almost all cases that the TR was reduced to less than 0.5 when the accumulated rain over consecutive days exceeded 15mm. Conversely there is the data for increases in TR during dry periods. Increases in TR were obtained for periods of 1,2,3 and 4 weeks without rain and the initial TR value was around 0.5. Fig. 7 (X-axis is TR, Y-axis is number of weeks without rain and Z-axis is Relative Frequency) is a probability distribution for these four cases. Only a small amount of data was available for periods greater than four weeks without rain and these values are all in the range 1.0 to 1.1 for a period up to 7 weeks. The data from Figure 7 was used to construct Fig. 8. The most likely values

of TR, that is the modal values for each marginal distribution were selected for Fig. 8. This relationship provides the key to establishing probability distributions for thermal resistivity from rainfall data over many years provided by the weather bureau. For periods of 5, 6 and 7 weeks without rain showed the same trend although only a limited amount of data was obtained. Thus values increases are shown up to a maximum of 1.1 at 6 weeks and do not change for 7 weeks. For dry periods greater than four weeks TR was assumed to be greater than 1.1. For the stabilised backfill monitored in this study, the normal assumption is that the TR will not exceed 1.2.
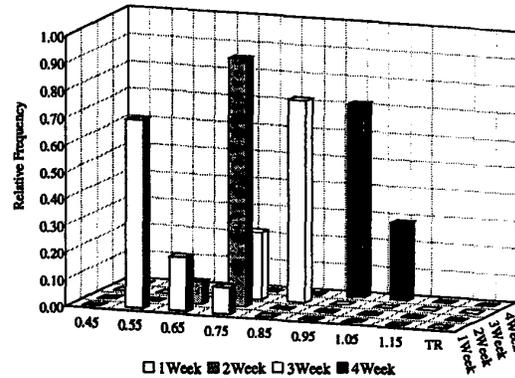

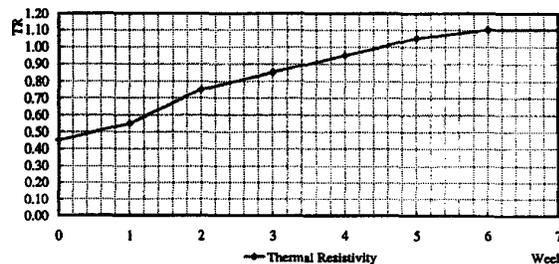Fig. 7. Probability of TR after a number of weeks without rain when soil has been saturated

Fig. 8. The most likelihood of TR vs number of weeks without rain

The above analysis establishes a quantitative link between rainfall and soil TR. This provides opportunity for short-term prediction of cable rating for operational purpose. For long term planning, it enables the use of rainfall statistics to predict seasonal or monthly TR probability distributions About hundred years of rainfall history in the Brisbane CBD from 1898 to the present was obtained from the Australian Bureau of Meteorology. From this data the probability distribution of the maximum number of weeks without rain during each month has been obtained. Figure 9 shows the result from January to December (The X-axis is number of weeks without rain and Y-axis is Relative Frequency). Normally November to March is during the "wet" season, and April to October is during "dry" season.
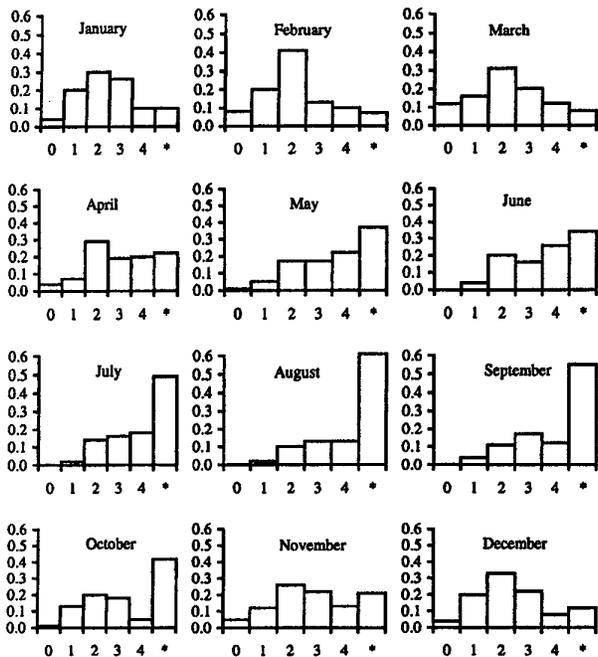
Fig. 9. Probability Distribution of the maximum number of weeks without rain during each month (0–4 means numbers of weeks without rain; * means more than 4 weeks without rain)
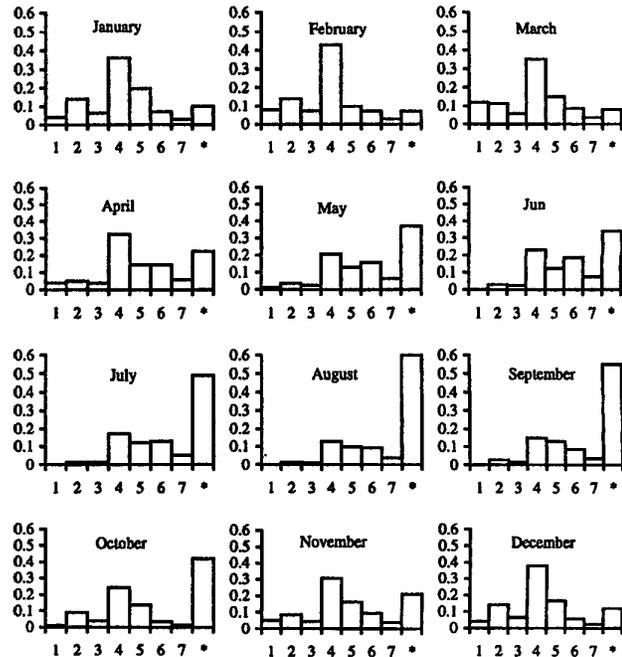

Fig. 10. Probability of the Maximum Value of TR during each month (1~7 means each section of TR value of 0.4-0.5, 0.5-0.6, 0.6-0.7, 0.7-0.8, 0.8-0.9, 0.9-1.0 and 1.0-1.1; * means more than 1.1)

Using the results of Fig.7 and Fig.9 a probability distribution for the most likely value of TR during each month can be established. It is plotted in Figure 10 (The X-axis the value of TR and Y-axis is Relative Frequency). The relative frequency for periods greater than four weeks will include periods of up to six months. For all these cases the thermal resistivity will be greater than 1.1. For studies of sandy soils this value could be 4.0 or higher. Obtaining this data from field trials may not be possible because of the limited number of times this may occur. However by measuring soil moisture content instead of TR, and then using the TR/moisture relationship this problem could be overcome.

V. DISCUSSION

The analysis in the previous section has shown that it is possible to establish experimental thermal resistivity probability distributions at a selected site from a program of daily field measurements of thermal resistivity and weather bureau rainfall records. With a distributed temperature system (DTS) for measuring cable temperatures along its route the above technique could be applied to obtain realistic data on soil TR at a cable "hot spot".

To establish the "hot spot" for a cable route without DTS a systematic approach to measurement and analysis similar to that described in this paper could be applied. Thus measurements at different sites along a cable route can provide data to compare the effects of different route conditions e.g. the effect of different soil types, topography, vegetation, sealed surfaces etc. There is evidence that such effects are important and such a study would provide quantitative data on their significance. Although there may be a doubt about the "hot spot" location, this would establish the characteristics of the thermal environment of a cable route and reduce the risk in decisions about soil TR.

Data similar to that obtained in this report improves on techniques currently available for assigning a value of thermal resistivity to a selected cable route. They show that soil TR can vary by a factor of two or more even in a period as short as one month (see Figure 4). Also the thermal resistivity can maintain a low value over an extended period for a regular rainfall pattern (see Figure 5). The probability distributions in Figure 10 show that in February the maximum value of TR can be expected to be less than 0.8 with a probability of 80%. For July the corresponding figure is 1.1. It thus provides more informed and precise basis for establishing the thermal resistivity in planning reinforcement of a circuit than reliance on a published recommended value. Thus for a cir-

cuit approaching its design load monitoring could be installed to establish the actual soil parameters and their expected variations over an extended period of time. Modern technology has reduced the cost of on line monitoring so that such studies are viable for a large range of cables for distribution and transmission circuits.

For operational situations advantage can be taken of the large variations that occur in TR. Thus the results in Figures 3 and 5 show consistently low values of TR for circuits near the Brisbane CBD. This provided the opportunity to delay reinforcement of the 11kV circuit that was approaching its capacity based on a TR of 1.2.

An aspect of asset management that can be addressed is ensuring that the cable is operating within its TR design limits. Choice of a realistic value of TR for a specific circuit has always presented problems because the limited knowledge about TR along a circuit and the expense of obtaining this data. However the use of automated monitoring using modern technology has reduced the cost of site monitoring and make it viable procedures similar to that described in this paper. A systematic monitoring procedure over a period of time would enable the collection of data for more informed decisions about soil TR. It also provides the opportunity to monitor the behaviour of special backfills to ensue that the anticipated behaviour occurs over a period of time.

VI. FUTURE RESEARCH

Future research would aim at establishing more reliable, realistic values of soil thermal parameters. These that are most important factors determining the cable rating. The need for better knowledge of the cable environment is highlighted even more with policies to achieve greater plant utilisation. Such policies can be achieved with reduced "safety factors" that require a more detailed knowledge of the cable environment. Another aspect is the importance of ensuring that plant is operating within its limits. Extended dry periods can lead to very high TR and consequent reduced ratings. Monitoring of the cable environment will provide early warning of such problems.

Inherent in the above research is the investigation of techniques to establish the "hot spot" along a cable route. For cables without distributed temperature sensing this is a major problem. However by installing monitoring stations at different locations along a route the relative behaviour can be examined and effects due to topography, vegetation etc. can be quantified to establish their importance. It may not be possible to establish a hot spot location with certainty, but a risk-based approach could be established.

The monitoring techniques described here are of course immediately applicable to on line ratings for operational purposes. By using actual parameters the true cable ratings are obtained rather than design values based on conservative assumptions due to lack of knowledge. The studies have shown that even small amounts of rain will usually result in low TR values. Thus for the 11kV cables studied above the low values of TR allowed the rating to be doubled during a period of high demand.

VII. CONCLUSION

The described technique provides a reliable and practical method for daily measurement of soil thermal parameters along underground cable routes. These measurements can be used to calculate actual ratings to take advantage of favourable ground conditions during periods of heavy load. It also provides the opportunity of correlating the field values of thermal resistivity with rainfall records. This paper shows how this data may be analysed to obtain probability distributions of thermal resistivity that can be used in planning studies. There appears to be no basic problem for its wider application but further studies are necessary to demonstrate this.

VIII. ACKNOWLEDGMENTS

IX. REFERENCES

[1] Anders, G.J. and M.M. Krpan. "Delaying investments in transmission facilities through cable uprating," Proceedings of International Conference on Large High Voltage Electric Systems, Paris, September 1988, Section 37-08.

[2] Anders, G.J., S.M. Foty, and S.J. Croall, "Cable environment analysis and the probabilistic approach to cable rating," IEEE Trans. Power Delivery, Vol.5, No. 3, July 1990, pp. 1628-1633.

[3] Thornthwaite, C.W., "An approach Toward a rational classification of climate," Geographical Review. Vol. 38. 1948.

[4] A.K. Blackwell, A.E. Davies, and C.L. Ong-Hall. "Forecasting cable ratings using a probabilistic method and real time parameter values," of AC and DC Power Transmission IEE Conference Publication, London, 1996, No.423 pp. 81-85.

[5] H.S. Carslaw, and J.G. Jaeger, Conduction of heat in solids. Xoford University Edition 2 ed. 1959.

[6] J.S. Lyall, G.Hubner, and K. Hoffman, "An alternative method for measuring soil thermal parameters for underground cables," in 3rd International Symposium on electricity distribution and energy management Conference, 1993, Singapore.

X. BIOGRAPHIES

Jim Lyall obtained his B.E., M.E. and PhD from the University of Queensland. He worked for power supply authorities and manufacturers in Australia and Europe over a period of 20 years. He then joined the Queensland University of Technology academic staff and has been involved in teaching, consulting and research associated with electromagnetics, power systems and machines and underground power cables. He is now a member of the Research Concentration in Electrical Engineering in the School of Electrical and Electronic Systems Engineering at the Queensland University of Technology

Ghavam Nourbakhsh obtained B.Sc. and M.Sc. in electrical engineering from California State University in Sacramento, U.S.A. He also obtained a M.Sc. research degree in the field of power system reliability from University of Saskatchiwan in Canada. He has worked for overseas utilities for five years. He is now an academic member of Research Centre for Electrical Energy in the School of Electrical and Electronics Engineering in Queensland University of Technology in Australia, for the last six years. His fields of interest are in power system reliability and maintenance. He has number of national and international publications in his fields.

Hua-Chun Zhao received his B.E. degree in Electrical System and Automation from Ho Hai University, China, in 1993. He has been working for power supply authorities in Nanjing China for over 5 years, where as an overall designer and project leader he has undertaken over 30 projects. These include 50km of overhead transmission line and 15km of underground power cables up to 220kV. Since May 1999, he joined the Research Concentration in Electrical Energy at the Queensland University of Technology, Australia. He is currently studying towards a MEng in the area of underground power cable environment monitoring and analysis.