TECHNICAL RECOMMENDATIONS FOR IMPLEMENTATION OF DYNAMIC CABLE RATING SYSTEM – CABLE MODELLING

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ABSTRACT

Dynamic Cable Rating (DCR) systems are an attractive solution to adopt by network operators to determine the real-time thermal ratings of underground cables and potentially operate them at a higher loading level. This paper provides an overview of existing DCR calculation methodologies with particular reference made to thermal electrical equivalent models which is the most established method for dynamic cable rating computation. Within this overview includes practical considerations and limitations of DCR methodologies and models with recommendations provided on how to implement and install Distributed Temperature Sensing (DTS) technology alongside DCR systems.

INTRODUCTION

There has been an increased trend in the electricity load growth and the connection of distributed generations in recent years. This has presented a challenge to network operators to unlock further network capacity without the need for disruptive and costly network reinforcement. Innovative solutions are therefore required to improve the utilisation of network assets. One such solution is to operate the network based on the real-time thermal rating of underground cables, implemented using DTS and DCR systems.

The interest in this solution has been growing recently with various network operators trialling different DCR systems. SP Energy Networks, a UK transmission network owner and distribution network operator, has trialled a DCR system as part of their innovation strategy. The project involved the installation of a DTS optical fibre system on four 33 kV windfarm circuits to compute the cable core temperature based on the thermal and electrical properties of the cable[1].

DCR systems offer the prospect of opening further network capacity without the need for network reinforcement. The system could also be expanded into Active Network Management (ANM) schemes to control the output of the distributed generation based on the real-time network capacity.

DCR systems determine the real-time current capacity of a power cable based on the real-time measurement of cable thermal properties and ambient temperatures, circuit loading and cable thermal model. A DCR system typically consists of two main components:

- A temperature monitoring technology providing temperature within close proximity of the underground cable. This is typically the DTS technology or a retrofitted temperature monitoring solution for a predetermined location along the cable.

- A DCR calculation engine which determines the cable conductor temperature based on the monitored temperature and the cable thermal characteristics.

This paper will mainly focus on second components of DCR system, the calculation engine, to provide an overview of existing DCR calculation methodologies, with particular importance on the thermal electrical equivalent models which is the most established method for dynamic cable rating computation. However, there are some practical considerations that the calculated thermal behaviour may not be a true representative of actual cable temperature due to: location of temperature sensors, circuit installation arrangements, and the presence of other heat sources external to the circuit e.g. other cable circuits. These conditions are also discussed and desktop study results are presented. In the next section also an overview on suitable DTS system for DCR application is discussed.

DTS Principle of Operation

DTS systems operate on Raman Scattering principles, by sending a laser light pulse down an optical fiber cable and collecting the back-scattered light [1]. The back-scattered light contains three spectral components, the Rayleigh scattering with wavelength of laser source, the Stokes component with the higher wavelength in which the photons are generated, and the Anti-Stokes components with a lower wavelength. The intensity of the Anti-Stokes

1 https://www.ofgem.gov.uk/sites/default/files/docs/2015/08/temp_monitoring_windfarm_cable_circuits_final_1.pdf

band is temperature dependent, while the Stokes band is temperature independent. The DTS system then uses the ratio of the Anti-Stokes and the Stokes to determine the local temperature measurement and the time of flight of the optical pulse to calculate the location of the temperature [2]. Figure 1 visualizes Raman Scattering principles.

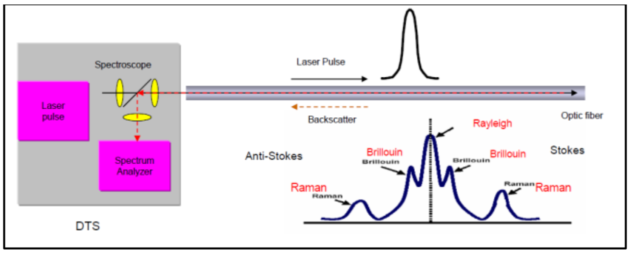

Figure 1 – DTS Utilisation of Raman Scattering

As the spatial scale of cable fault points (areas of cable defects), is from one to several meters, it is recommended that the sampling distance of DTS systems should be no more than 1 meter, with a spatial temperature resolution no more than 2 meters. Temperature detection should have a maximum error, at the most remote fiber end, less than 1 °C in a standard test cycle. DTS systems can also be used to actively support the diagnosis, protection, and maintenance of cable system defects through two conventional methods; the peak temperature and the peak temperature rise rate.

The peak temperature rise is performed using Spatial Peak Detection (SPD). A cable fault shows itself as the peak of the M-spatial scale in the distributed temperatures. SPD utilises a wavelet filtering algorithm with the function of recognizing temperature peaks to mitigate the following normal temperature changes:

- Overall temperature change of the cable
- Temperature changes of partial large regions
- Temperature rise step (two environmental interfaces, sudden increase of fiber attenuation
- Large-scale temperature gradient

Before the SPD operation, the distributed temperature rise is the distribution of the peak temperature rise on the M-spatial scale, and the distribution of the peak temperature rise also includes the environmental noise. The peak temperature recorded are compared to their own historic temperature, and also against temperatures of neighboring sections.

Peak temperature rise rate is achieved through utilization of multi-time scale scanning (MTS), which filters out the normal cable fluctuations by monitoring multiple time intervals; Previous 5-10 minutes, 2 Hours, or 24 Hours. Information regarding the abnormal temperature rise of the cable within the interval periods is advantageous in detecting the potential points of failure. MTS is required to adopt the optimized data cache programs to ensure all time scales receive the real-time update, while cache of historical data is minimized [3].

DCR CALCULATION METHODOLOGIES

A DCR system uses DTS data (cable proximity temperature) to calculate the cable core temperature of a circuit by considering the cable structure, thermal and electrical properties, electrical-influencing factors, and environmental conditions.

The core temperature of a cable is calculated using either steady state or dynamic current rating methodologies and can be based on several different models, including; thermal electrical equivalent models, steady state discrete thermal models, finite element analysis, or continuous heat transfer models. The most widely used and trusted method is the discrete thermal models proposed by Neher and McGrath [4] which is the foundation for IEEE and IEC standards for steady state current rating [5]. For dynamic cable rating however, the most established method for rating computation is the thermal-electrical analogy which influenced the IEC 60853 standards [6].

Thermal Electrical Mathematical Model

Thermal-electrical models are designed based on the analogous properties of heat flowing in a thermal circuit and current flow in an electrical circuit i.e. The thermal-electrical analogy (TEA). The application of TEA allows for ohms law to be utilized; where temperature, heat flow and thermal impedance behave the same as voltage, current and electrical impedance respectively.

The model considers each layer of a cable as a thermal resistance, thermal capacitance, and heat sources as current sources. Thermal resistance is defined as the material's ability to impede heat flow and thermal capacitance refers to the material's ability to store heat.

The thermal resistances of the layers between the cable's conductor and environment are connected in series, with shunt thermal capacitances and heat sources. Heat transfer through the thermal resistances raises the temperature gradient between the two sides of the thermal resistance, and heat flow injected into capacitors varies with temperature through time. The sum of the temperature gradients determines the total temperature difference

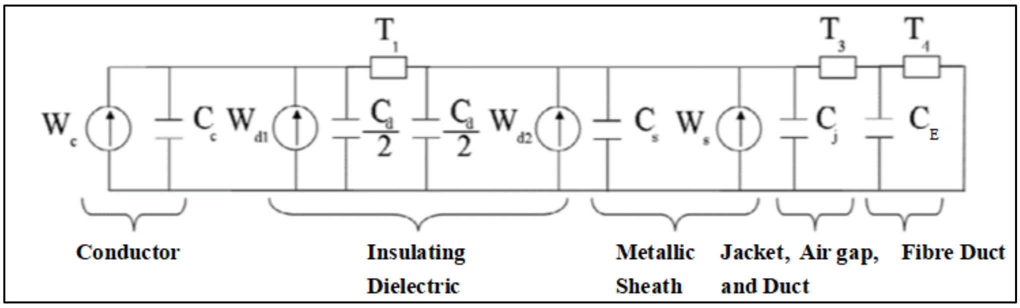

Figure 2 – Thermal Electric Analogy [7] [8]

between the environment and the conductor. Figure 2 provides shows the TEA model. Heat sources are incorporated by modelling the cable subcomponents losses, allowing for the temperature at the different layers to be calculated.

Steady State Model

A steady state model can be obtained which utilises the thermal-electrical analogy model. This is based on IEC 60287. The algorithm for calculating the core temperature in the steady-state engine is shown in (1).

$$\Delta\theta = \left[W_c + \frac{W_d}{2}\right] \cdot T_1 + [W_c \cdot (1+\lambda_1) + W_d] \cdot n \cdot T_2 + [W_c \cdot (1+\lambda_1+\lambda_2) + W_d] \cdot n \cdot (T_3 + T_4) \quad (1)$$

- $\Delta\theta$ – Conductor temperature rise above the ambient temperature (°C)
- W_c – Core losses per unit length (W/m)
- W_d – Dielectric losses, for the insulation and Semiconductive layers (°C W/m)
- T_1 – Thermal resistance between the conductor and the sheath (°C W/m)
- T_2 – Thermal resistance of the medium inside pipe-type systems (°C W/m)
- T_3 – Thermal resistance for the external serving of the cable (°C W/m)
- T_4 – Thermal resistance of the surrounding medium (°C W/m)
- λ_1 – Sheath loss rate, ratio of losses in the metallic sheath to conductor losses (–)
- λ_2 – Armour loss rate, ratio of losses in the armour to conductor losses (–)
- n – Number of load-carrying conductors per cable

Given that $\Delta\theta = \theta_{Core} - \theta_{Ambient}$, where the ambient temperature is equal to the fibre temperature, the core temperature could be easily calculated for a series of steady state points.

Dynamic Model

A dynamic model can be constructed based on a 3-node analytical system to represent a TEA circuit adopted by [8] [9]. This involved the grouping of thermal resistances and capacitances into three respective regions, where subscripts are; Conductor (c), Dielectric tape (d1 and d2), Insulation (XLPE), Sheath/Screen (S), Jacket (J), Air Gap (AG), Cable Duct (CD), and Fiber Duct (FD).

The thermal resistance and capacitance grouping regions are outlined in Figure 3. Region 2 is the thermal properties of the medium inside pipe-type systems, however as the cable under consideration is not laid in a pipe, this was neglected ($T_2 = 0$, $C_2 = 0$). It should be noted that the dynamic engine incorporates the cable modelling, configuration, and loss methodologies expressed in IEC 60287 and IEC 60853.

For thermal resistance:

- Region 1 – sum of the thermal resistances of dielectric layers ($T_1 = T_{XLPE} + T_{d1} + T_{d2}$)
- Region 3 – sum of the sheath, jacket, cable duct and air gap thermal resistances ($T_3 = T_S + T_J + T_{AG} + T_{CD}$).
- Region 4 – thermal resistance of the optical fibre duct ($T_4 = T_{FD}$).

For thermal capacitance:

- Region 1 – combination of the conductor and half the dielectric thermal capacitances ($C_1 = C_c + C_{d1}$).
- Region 3 – combination of screen, jacket and half the dielectric thermal capacitances ($C_3 = C_{d2} + C_S + C_J$).
- Region 4 – combination of the cable's duct, airgap, and the fibre's duct ($C_4 = C_{CD} + C_{AG} + C_{FD}$).

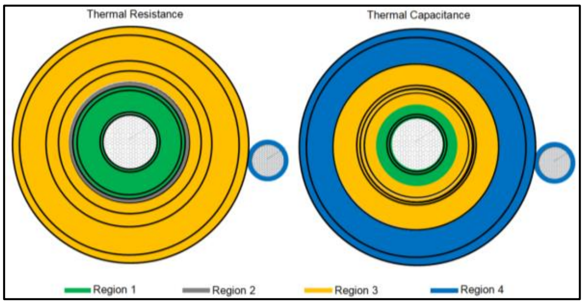

Figure 3 – Thermal Resistance and Capacitance Grouping Regions

The methodology provided by [8] [9] can dynamically calculate the current loading with respect to time with the implementation of a set of first-order differential equations in matrix form, shown in (2). These equations were developed on the 3-node analytical system however increasing the number of nodes would proportionally increase the size of the matrix.

$$\begin{bmatrix}\dot{\theta}_J\\ \dot{\theta}_S\\ \dot{\theta}_C\end{bmatrix} = \begin{bmatrix} -\left(\frac{1}{C_4T_3}+\frac{1}{C_4T_4}\right) & \frac{1}{C_4T_3} & 0 \\ \frac{1}{C_3T_3} & -\left(\frac{1}{C_3T_1}+\frac{1}{C_3T_3}\right) & \frac{1}{C_3T_1} \\ 0 & \frac{1}{C_1T_1} & -\frac{1}{C_1T_1}\end{bmatrix} \cdot \begin{bmatrix}\theta_{Ref,J}\\ \theta_{Ref,S}\\ \theta_{Ref,C}\end{bmatrix} + \begin{bmatrix}\frac{1}{C_4T_4}\cdot\theta_{Fibre}\\ \frac{1}{C_3}\cdot(W_{d2}+W_S)\\ \frac{1}{C_1}\cdot(W_{d1}+W_C)\end{bmatrix} \quad (2)$$

Considering (2) from left to right:

- Matrix 1 ($\dot{\theta}$) – Temperature rate of change for each layer (°C/s).
- Matrix 2 (A) – Covariance matrix and defines the thermal properties of each region (1/s).
- Matrix 3 (θ_{Ref}) – Reference temperature matrix (°C).
- Matrix 4 ($\dot{Q}$) – Represents the respective heat sources of each layer (°C/s).

The first order differential equations in (2) can be solved using indefinite integration involving eigenvalues and eigenvectors. However, the load data and optical fibre temperature data (from the DTS) have associated time stamps, which can be used to calculate the time between temperature steps and hence solve the equations through a linearization approach.

With reference to equation (3), a simplified representation of (2), k is the real-time timestep and temperature rate of change ($\dot{\theta}$) is expressed as ($\partial\theta/\partial t$). The time interval ($\partial t$) between the real-time timestep and the previous timestep is however known from data provided by the DTS. The reference temperature (θ_{Ref}) is also known as its the previously calculated temperature of each node. For the first iteration this is set equal to the optical fiber temperature. The heat source variable (matrix 4 – $\dot{Q}$) is also known as the dielectric, sheath and core losses are dynamically calculated at each timestep, and θ_{Fibre} is provided by the DTS – leaving the real-time temperature (θ_k) as the only unknown. Equation (3) can therefore be rearranged by grouping the knowns and unknowns, shown (4).

$$\frac{\partial\theta}{\partial t} = \frac{\theta_k-\theta_{Ref}}{t_k-t_{Ref}} = A\cdot\theta_{Ref}+\dot{Q} \quad (3)$$

$$\theta_k = \left(A\cdot\theta_{Ref}+\dot{Q}\right)\cdot\partial t+\theta_{Ref} \quad (4)$$

$$\begin{bmatrix}\theta_J\\ \theta_S\\ \theta_C\end{bmatrix} = \left(\begin{bmatrix} -\left(\frac{1}{C_4T_3}+\frac{1}{C_4T_4}\right) & \frac{1}{C_4T_3} & 0 \\ \frac{1}{C_3T_3} & -\left(\frac{1}{C_3T_1}+\frac{1}{C_3T_3}\right) & \frac{1}{C_3T_1} \\ 0 & \frac{1}{C_1T_1} & -\frac{1}{C_1T_1}\end{bmatrix} \cdot \begin{bmatrix}\theta_{Ref,J}\\ \theta_{Ref,S}\\ \theta_{Ref,C}\end{bmatrix} + \begin{bmatrix}\frac{1}{C_4T_4}\cdot\theta_{Fibre}\\ \frac{1}{C_3}\cdot(W_{d2}+W_S)\\ \frac{1}{C_1}\cdot(W_{d1}+W_C)\end{bmatrix}\right)\cdot\partial t + \begin{bmatrix}\theta_{Ref,J}\\ \theta_{Ref,S}\\ \theta_{Ref,C}\end{bmatrix} \quad (5)$$

The methodology described was used to calculate DCR values of a 33kV underground cable circuit dedicated to a wind farm fitted with DTS system as part of innovation project conducted by SPEN. The results are shown in Figure 4.

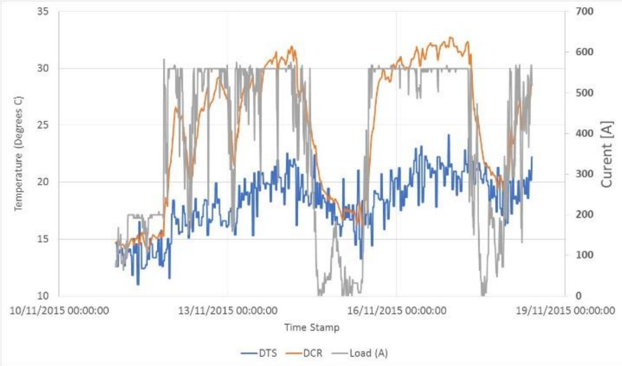

Figure 4-

RECOMMENDED FIBER LOCATION

DCR is highly dependent on inputs provided by the DT and correct construction of the cable model. Underground cables may be laid in the ground in different arrangements such as ducted or un-ducted, flat or trefoil formation etc. In order to provide a fit for purpose temperature data, it is important to position of the optical fibre at the hottest regions surrounding cable configurations. However, this may not necessarily achievable due to installation limitations and also protection required for fiber optic for any physical damage. Figure 5 shows the recommended fibre locations in different cable installation arrangements.

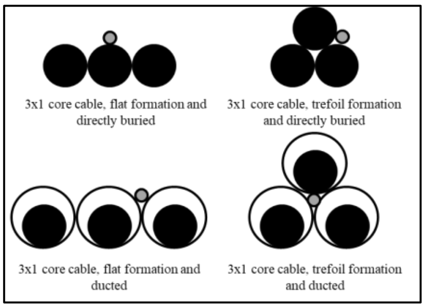

Figure 5 – Cable Configurations

The cable configurations in Figure 4 were analysed using the CYMCAP software. The studies followed the general installation conditions, however the burial depth was set to 800 mm of the centre of the trefoil with circuit spacing of 50 mm. The steady state analysis study featured equally loaded cables of 700 A with a unity load factor. The results of these studies are shown in Figure 5.

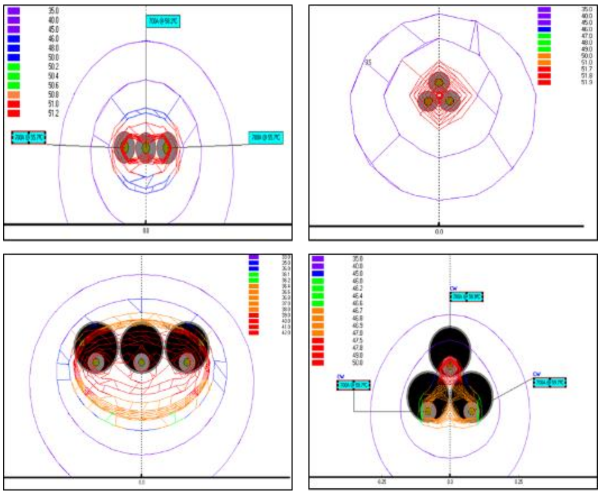

Figure 5 – CYMCAP results for heat distribution in different cable configurations

The results are shown in Figure 5, it was found that an installation of a micro-duct in the center of a trefoil captures the hottest region surrounding the cable. By positioning the optical fiber in this arrangement, a conservative approach can be taken to calculate the temperature of the conductor core. The studies also provided recommendations regarding circuit configuration arrangements, concluding that a trefoil cable configuration capture the most accurate thermal behavior of single circuits in groups.

CONSIDERATION POINTS FOR DCR CALCULATION

There were a number of issues that may be considered for modelling and DCR calculation which included:

- The DCR assumes perfect contact between each layer with no abnormalities, however it does contain procedures to mitigate the effect of cable abnormalities.
- In case of other heat sources, such as an adjacent circuit, the fibre shall be installed the closest possible to the cable core which is exposed the most to the heat source. This will ensure the calculated DCR values are fit-for-purpose and reflect the "close to reality" situation.
- In a 3 core circuit, the DCR can only determine the temperature of one cable and equal temperature is assumed across all three cables. The contribution of all three cables is however reflected in the temperature recorded by the optical fibre.
- The DCR assumed the measured temperature from the optical fibre to be uniform around the entire external surface of the cable, while the optical fibre can only capture the temperature of a single reference point.
- Modelling of the cable circuits shall represent the installation arrangement at the thermal pinch points along the cable circuits. This requires a process of identifying high temperatures suggested by the DTS data and match the locations with the installation records to construct the thermal model.

CONCLUSION

This paper has provided an overview of DCR and DTS systems and explained methodologies to implement them. Particular attention was given to the thermal-electrical analogy model which contained a method to accurately determine the cable core temperature for both steady state and dynamic systems, utilising first order differential equations and linear optimisation. Recommendations were then provided which detailed that Trefoil circuits (in flat formation for circuits with shared trenches) are the ideal installation configuration for the optical fiber dependent DTS system. Considering an accurate representative model of the thermal pinch points are essential to ensure the calculated DCR values adequately accurate for network operation.

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