Principle of DTS based Real Time Thermal Rating (RTTR) System

This technical note provides details of the Real Time Thermal Rating (RTTR) system by Bandweaver. It goes into details of both the theory and thermal calculations and also provides details on the practicalities for the design, qualification and implementation of the RTTR system.

The Bandweaver RTTR system incorporates multiple functions, including:

- Cable load, cable fault and thermal characteristics of the cable environment
- Cable online monitoring scheme based on Distributed Temperature Sensor (DTS) technology
- Ability to track the thermal bottleneck point of the cable
- Dynamic Cable Rating model (DCR) to calculate the cable conductor temperature (T_{CC}),
- Short-term emergency load
- 48 hour prediction based on future load prediction

BACKGROUND

With the rapid expansion of cities' underground cable layouts as well as the continuous increase of higher voltage systems, the safety and maintenance issues of power operations becomes increasingly prominent. These issues include:

- **Load safety:** Thermal conditions of ground surface and underground in cities are complex and multi-circuits layout becomes common. These uncertainties and complexities introduce risk into the current rating calculations based on IEC60287. Because of this high level of uncertainty, operators have a tendency to take a conservative approach and operate the power cables with a low utilization rate.

- **Cable fault:** It is critical to locate faults as early as possible so that the maintenance department can take timely actions to minimize possible losses. Some cases show that delayed cable fault detection has led to increased fire safety risks.

ROLE OF DISTRIBUTED TEMPERATURE SENSING

DTS technology has increasingly been used for cable temperature monitoring in recent years. The emergence of DTS has enabled a continuous thermal profile along the length of the cable. When this profile is combined with reliable cable load data this enables the operator to have a complete understanding of how the environment is affecting the cable from a thermal standpoint and uncertainty factors of the environment are greatly reduced.

The sensing fiber can be installed in a number of possible configurations, including on the surface of the cable or in the protective layer of the cable during the cable fabrication process, within the cable bundle configuration or even in ducts run alongside the power cable. The Bandweaver RTTR has the flexibility to take into account the different configuration of the sensing cable position.

THERMAL CHARACTERISTICS OF POWER CABLES

With the cable surface as the boundary, the cable interior constitutes a thermal system which includes the following three heat sources in the normal operation:

1. Conductor Loss $$Wc = I^2 \cdot R_0 \cdot [1 + \alpha_{20}(Tcc - 20)] \cdot (1 + Ys + Yp)$$

- *I = current;*
  R0 = DC resistance of conductor at 20ºC;
- *α20 = TCR (Temperature Coefficient of Resistance) of conductor materials;*
- *Tcc = temperature of the conductor;*
- *Ys = skin effect factor;*
- *Yp = proximity effect factor.*

R0, α20 and *Ys* are determined by the cable construction materials and power frequency. *Yp* is also affected by the cables' spatial relationship. For installed cables, these parameters are all determinate. Conductor loss is a function of the two real-time variables: current and conductor temperature. Due to the resistance temperature effect of the copper, the conductor loss becomes larger while the conductor temperature rises under a fixed load. Conductor loss is the major heat source of the cable with the magnitude as 10W/m; Because the thermal conductivity of the conductor is very small in comparison with that of the outer insulation material, the conductor can be regarded as a single thermal unit, and is evenly heated by the conductor loss.

2. Dielectric Loss $Wd = 2\pi \cdot f \cdot c \cdot U_0^2 \cdot tg\delta$

- *f = power frequency*
- *c =cable electric capacitance,*
- *U0 - phase voltage,*
- *tgδ = insulation loss factor under the power system and working temperature;*

Thus, dielectric loss is a constant under specific power conditions and irrelevant to the load current. For cables over 220kV, dielectric loss can achieve the same magnitude as the conductor loss. The loss is not evenly distributed in the insulation. The distribution density is a function of the electric-field intensity and is higher near around the conductor. Related IEC method distributes half of the total dielectric loss respectively at the inner and outer edges of the insulating layer. Calculation shows that the method is accurate for a static calculation. However, in the dynamic calculation which requires higher precision, the distribution characteristics of the dielectric loss in the insulating layer must be considered.

3. Sheath Loss

Sheath loss correlates to the phase arrangement of its own and neighboring circuits. In the cases of single end grounding or well balanced cross-grounding, the loss is quite low; While in contrary circumstances, a significant sheath circulation could be caused and the loss may be great. The designer of the circuit should provide the relevant calculation. An on-site measurement is required to obtain the level of circulation as necessary and the loss could be estimated then.

According to above analysis, overall calorific generation of cable is determined by:

- cable structure, including geometric parameters and material properties of the conductor and all layers;
- load variables, including current, voltage and frequency;
- phase spatial relations with other cables;
- conductor temperature;

Therefore, for installed cables, phase spatial relations with other cables, the load voltage and frequency have all been determined; The total heat of cables is only correlated to the current, and the conductor temperature. It should be noted that if the load current contains high order harmonic generation, both skin effect and dielectric loss will increase and the cable generates extra heat.

HEAT CONDUCTION

The heat transfer mode inside the cable is conduction. IEC60287 offers the heat capacity and thermal resistance of commonly used cable materials. Thermal properties of these materials remain constant within the range of working temperature. Tests show that these assumptions are reliable. Nonetheless, IEC60287 does not consider the air gap which may exists in the cable structure. In large cross-section cables, the air gap is often introduced on both sides of the metal sheath owing to the design or process limitations. Heat transfer of the air gap involves both heat conduction and radiation. Resistance of radiation is the function of temperatures on two surfaces. While the heat flow increases, this resistance decreases. In addition, due to the thermal expansion effect of plastic material, the air gap usually becomes thinner and then the conduction resistance becomes smaller when the cable warms up.

Total thermal resistances of the cable under the rated or medium-load status can be obtained through empirical means and then air gap resistance can be calculated under the two different heat flow conditions. To be conservative, the greater value should be taken. Evidence shows that the magnitude of the resistance of an air gap of about 0.1mm wide is of 0.01 W/K*m; Those of 0.5-2.0mm width may reach 0.1 W / K * m. Comparing with the total thermal resistance of the cable, the variation of the air-gap thermal resistance affected by heat flow and temperature is small, so it can be considered that the internal thermal conductivity of the cable is only determined by the cable structure, that is, for the specific cable, its thermal resistance keeps constant.

It is noteworthy that heat conductive abilities along the axial direction and radial direction of the cable are very different. The former is much smaller due to the excellent conductivity of conductor and sheath materials, usually 2-3 magnitude less than the latter which is mainly constructed by non-metallic materials.

If the single-core coaxial cable is continuous and its heat-dissipating conditions along the length and in all

directions of cable surface are identical, the internal temperature of the cable only changes in the radial direction; Its heat transfer model can be simplified as a one-dimensional mathematic problem. However, it is almost impossible to require a complete identity of heat-dissipating conditions in all directions of cable surface. For example, for a single-core cable stacked in a trefoil-shape, heat-dissipating conditions near the surface of the other two cables are relatively poor. But if the metal sheath is thick enough, compared with the cable surface and exterior as well as insulating layer, its low thermal resistance and high heat capacity tend to create a good thermal unit to maintain the one-dimensional characteristics for the interior. The opposite circumstance or the three-core cable case is a two-dimensional thermal conductivity issue and the mathematical treatment is much more difficult. IEC provides an equivalent conversion method to turn the three-core cable problem into one of single-core cable, which in fact simplifies the two-dimensional problem into one-dimensional. Both IEC60287 and the subsequent cable load models are one-dimensional models.

DISCONTINUITY POINTS

Under uniform environmental conditions, the cable has identical calorific generation and thermal resistance in all places and the cable conductor or surface temperatures remain same along its length. But cable system itself is not perfect and has thermal discontinuity points

Fault Heat Source

Disregarding the induction loss due to improper design, fault heat sources include:

- Resistive heat source caused by large joint resistance of the conductor in accessories. The heat source acts on the conductor;
- Insulation defects / heat of partial discharge. Strong and sustained partial discharge currently observed may lead to thermal effects, whose heat source lies in the insulating layer.

Resistive heat source and the heat source of partial discharge (both classified as a deep heat source) which occurs in the insulating layer near the conductor propogate along the conductor and metal sheath in the axial direction and passing all non-metallic layers of the cable in the radial direction. Axial resistance is about 3 orders of magnitude less than the radial resistance. The heat source of partial discharge which occurs in the insulating layer near the metal sheath is classified as shallow heat source. Its axial resistance is led by the metal sheath and radial resistance led by each non-metallic layer outside the insulating layer, the former being about 2 orders of magnitude smaller than the latter. Temperature distortion formed by deep and shallow heat sources can respectively reach meter-spatial scale and decimeter-spatial scale on the cable surface along the axis.

Cable Accessories

The outside diameter of the cable accessory is large and the thermal resistance between the accessory surface and its environment is smaller than that of the cable body; when the crimping resistance is normal and no abnormal heat is generated, the surface temperature of the accessory is usually lower than that of the cable body. Comparing with the cable body, the accessory has the larger internal thermal transfer resistance and smaller surface thermal transfer resistance (in air or water). For an accessory of larger size, the differences between its conductor temperature and the cable body temperature need to be obtained through computation or experiment. But usually, after taking into account the axial thermal conductivity of the cable, the conductor temperature in accessories should be close to that of the neighboring cable. This also gives a hint: if the accessory has abnormal resistive heat source, it may be more effective to detect whether there is abnormal temperature rise in cables on both sides than to detect directly the surface temperature of accessories.

THERMAL CHARACTERISTICS OF THE CABLE ENVIRONMENT

The environmental conditions of the cable are complex. A cable may pass through a variety of layout environments; heat-dissipating conditions of each environment may not be completely uniform. In addition, cables usually need to pass through building structures, firewalls etc. Non-uniformity of environmental conditions is the leading cause of temperature changes along the length of the cable.

At present, the most comment cable layout environments are as follows:

a) Cable tunnels: in order to conduct heat exchange between the cable surface and the air inside the tunnel the heat transfer model needs to combine convection and radiation.
b) Direct burial: the mode of heat conduction is dissipation of heat to the surrounding soil.
c) Piping: in this cases there is air or water in the narrow space between the cable surface and the piping inner surface. If it is air, convection and radiation coexist; if it is water, only convection exists. Outside the piping, the mode is heat conduction. As the amount of fluid is small, the heat transfer mode of the piping is closer to heat conduction from a macro perspective.

In practice specific cable environments may show the following characteristics:

- For buried cables, the distributed temperatures may show an irregular profile due to the changing characteristics of the surrounding soil. For a tunnel, the air flow and ventilation conditions lead to the uniformity of its cable distributed temperature being smoother in comparison with direct burial or piping.
- For a cable at the junction of two environments, distributed temperature curve step and temperature rise curve step will be usually formed because of the macro differences of heat-dissipating conditions.
- In cases of passing through firewall and building structures etc., discontinuity points or sections will usually appear on the distributed temperature curve, due to the large difference between the heat conduction conditions between the different environments.
- In joint wells, terminals, maintenance channels, vents and drainage locations etc., the heat conduction conditions and environments are quite different and are vulnerable to weather conditions (a natural heat source). A case is illustrated in the following graph:

Example of temperature effect of cable wells

For the graph above the lower traces shows the distributed temperature trace (left axis) and the upper trace shows the temperature change in the last 2 hours (right axis). The sections or points with significant temperature change are all located at the cable wells;.

- Surrounding cables / circuits can be regarded as environmental heat sources. The size of the heat source is determined by related cable load current and can be very uncertain. But due to the parallel layout relationship, their mutual impact is integrated; other external heat sources, such as urban underground pipelines, subways, traffic tunnels etc. usually maintain a certain distance from the cable system, and the middle heat buffer layer is thick so that the impact on the cable is spread over larger distances
- Fire hazards are the result of an extreme environmental heat source. This may be caused by other equipment or events or by ineffective cable insulation. Studies on the development of fire in cable tunnels show that there is normally a stage prior to extensive propagation of flames. During this period, the hot air and smoke of local ignition points rise and accumulate at the top of the tunnel. While the hot air is rising it heats up the surrounding air, and shapes a smoke layer with a great volume and the absolute temperature is not very high.

DTS-BASED CABLE MONITORING METHODS

Requirements for DTS Parameters

As the spatial scale of cable fault points is typically in the range of 1 meter to several meters, the sampling distance of DTS distributed temperature should be no more than 1.0 meter, spatial temperature resolution no more than 1.0-2.0 meters, and temperature detection error at the most remote fiber end less than 1.0ºC in a standard test cycle. Because fault discovery mechanism based on distributed temperature is distinguished from traditional methods of fire alarm, inspection cycle of DTS can be set longer usually from 1 to 5 minutes. The aforementioned DTS parameters also meet the requirements of the load monitoring.

For critical tunnels, a specific sensing fiber will be used solely as a fire detector. This is typically positioned at the top of the tunnel to detect the temperature of the smoke layer. As the spatial scale of the smoke layer is large, the spatial resolution of the DTS can be 2.0 to 6.0 meters; detection cycle set around 10s, and the maximum temperature and temperature rise rate alarm threshold adopting international linear heat detection standards.

Fault Monitoring

Fault monitoring is the most fundamental and essential task of cable monitoring. According to the thermal characteristics of cable defects, the temperatures or changes of fault points act differently from surrounding normal cable sections. Through the discovery and location of temperature anomalies, we can effectively support the diagnosis, protection and maintenance of cable system defects.

The input of fault monitoring is the distributed temperature of the cable surface detected by DTS. Although resistive fault performance is closely related to the working current of the cable, the latter is not taken as the input condition because:

- Heat generation of insulation defect is of little relevance to the working current;
- The overall change of the distributed temperature has included the relevant information of the working current;
- The weather change completely unrelated to the resistive defect performance often shows a strong correlation with the current.

The output of fault monitoring can be specifically described as:

- Discovering and locating fire and significant temperature anomaly at the earliest time; sending alarm, dispatching personnel to take emergent measures; providing accurate location of trouble for emergency repair staff; tracking the development of trouble;

- Discovering and locating potential temperature anomaly; sending prompts or warnings, providing accurate location of trouble for the maintenance personnel; tracking the development of trouble.

Conventional monitoring methods usually include two basic monitoring indicators: the highest temperature and the highest temperature rise rate. High-level detection functions include:

SPD: Spatial Peak Detection (Peak Temperature Rise)

According to its thermal characteristics, cable fault shows as a peak of the M-spatial scale in the distributed temperatures. SPD Spatial Peak Detection method is the wavelet filtering algorithm with the function of recognizing such peaks. Applying SPD to deal with the distributed temperature rise curve may filter out the following normal temperature change:

- Overall temperature change of the cable (the load changes of the cable itself or its neighboring cable);
- Temperature changes of partial large regions (the tunnel ventilation);
- Temperature rise step (two environmental interfaces, sudden increase of attenuation at a fiber point);
- Large-scale temperature gradient (gradual change of environmental conditions).

The distributed temperature rise after being processed by SPD is the distribution of the peak temperature rise on the M-spatial scale. Accordingly, a new type of alarm indicators can be set: the rate of peak temperature rise. The distribution of the peak temperature rise also includes the environmental noise on the same spatial scale and is impacted by the weather (in the joint wells, terminals, maintenance channels, vents, drainage etc.) or by partial dissipation conditions (e.g. in the firewall, construction structure etc.). Therefore, setting the alarm threshold of peak temperature rise rate should consider the impact of aforementioned environmental noise.

Peak temperature rise rate achieves such a monitoring effect: the temperatures of all points are compared not only with the history of their own temperatures, but also with the temperatures of neighboring sections. Comparing with the conventional temperature rise rate indicators, it provides a highly targeted alarm mechanism.

MTS: multi-time scale scanning

As SPD can effectively filter out the normal cable temperature fluctuations, the monitoring indicators of peak temperature rise rate can be achieved respectively on multi-time scales, such as:

- the last 5 to 10 minutes;
- the last 2 hours;
- the last 24 hours;

This indicates that access to the abnormal temperature rise of the cable within the aforementioned length of time is especially advantageous in detecting the potential points of failure. The alarm threshold of the above different indicators of peak temperature rise rate can first be set around 2.5ºC -5.0ºC and then can be adjusted according to the actual ambient temperature noise level.

MTS is required to adopt the optimized data cache programs to ensure that the peak temperature rise rate on all time scales may receive the real-time update, and in the meantime, the cache of historical data is minimized.

LOAD MONITORING

Cable Current Rating and Model

Current Rating refers to the maximum current through the cable in a particular environment, under the permitted working temperature of the cable and within a given duration. The concepts defining the calculation model types

of current rating include: boundary, structure and status, in which the boundary of the model determines the time scale applied to the model.

Static current rating is calculated with the distant environment as the boundary, the model structure including the cable and surrounding environment, the current being a constant value, and the duration being unlimited. Static current rating calculation is a necessary means guaranteeing the long-term safe operation of cables in the design stage of cable circuits. If the calculation is correct, in the cable operational phase, the cable temperature is guaranteed not to surpass the permitted working temperature as long as the load is less than the static current rating. It is noteworthy that environmental conditions are included in the computation model. As environmental conditions are uncertain, the most conservative assumptions must be made in the calculation. But the most conservative assumptions are inferred based on limited information and cannot guarantee to cope with the complex actual operation environment. In addition, it is impossible for IEC to offer formulas of static current rating calculation for all layout situations.

Static current rating calculation requires the following information:

- Cable structure (excl. heat capacity);
- Electrical influence between circuits/cables;
- Thermal influence between circuits/ cables;
- Heat-dissipating conditions of the environment;
- Boundary temperature.

Quasi-dynamic current rating calculation refers to one in which certain parameters (such as the boundary temperature) required for the steady calculation are taken as variables to obtain the function of such variables of static current rating. For example, using the ambient temperatures of winter and summer to respectively calculate the current rating for these situations. Another application with higher dynamic capacity is to calculate the latest cable current rating through testing the air temperature of the cable tunnel.

Static current rating calculation has a characteristic irrelevant to states. The contrary situation can be called as **dynamic current rating (DCR)** calculation, which may not only involve the information required for the calculation of dynamic current rating, but also involve:

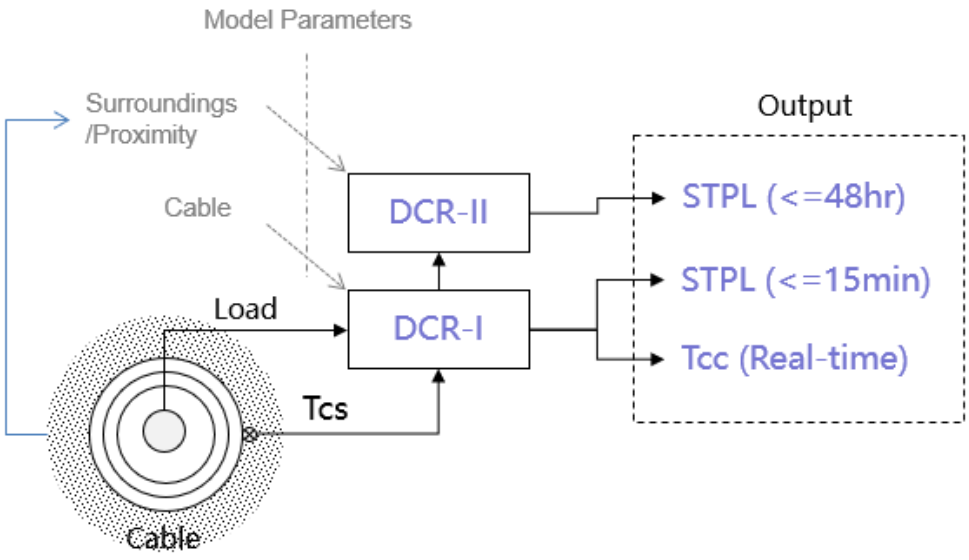
- Heat capacity of the cable structure;
- Cable internal temperature field/ state;
- Environmental temperature field/ state.

The heat transfer mathematical model which establishes the time variables for the cable and its environment is called the DCR model. It can calculate the current rating in a variety of initial states and durations and can also run a simulation. As long as the future load current curve is given, we can predict the future changing processes which include that of temperature field of cable conductor temperature.

Since the duration of thermal effect determines the spatial distance of the thermal effect, heat exchange does not occur in the far distance when the duration is short. Therefore, the calculation of short-term current rating does not require the environmental information or only needs the information of vicinal environment. Short-term emergency load belongs to this case. Another extreme example is the short-circuit current, which can be calculated merely with cable conductor parameters and temperature. Conversely, knowing the environmental information on a greater scope near the cable, we can conduct the dynamic current rating calculation or running simulation on a longer-time scale. DCR model can determine different spatial boundaries according to the calculated time scales of different requirements.

Before the appearance of DTS, DCR calculations were mainly used for transient and cyclical load calculation; similar to the calculation of static current rating, DCR calculation possesses uncertainty. When the model boundary is set in the distant environment, the model must include the uncertain cable environmental parameters, usually selecting the most adverse conditions; when the boundary is set inside the cable, on the cable surface or nearby, the model parameters are basically determined, but the boundary conditions are unknown, hence a risky assumption is required.

The application of DTS has for the first time created conditions for establishing a fully determinate (partial, irrelevant with the environment) DCR model. Optical fiber for temperature measurement is laid out on the surface or the protection layer of cables, performing a real-time detection of the temperature of cable surface or protection layer; and taking it as the boundary, the structure parameters within the DCR model only involve with the cable structure and the electrical-influencing factors of the surrounding cables, and the latter has been identified after the completion of cable layout. The DCR model with its boundary on the cable protection layer or cable surface is called the DCR-I model or internal model. Because the model parameters and boundary conditions are determinate, DCR-I model can reliably calculate the temperature field within the boundaries (including the conductor temperature). Through analyzing the responsive relationship between cable gross calorific power and boundary temperature, and identifying the thermal parameters and status of surrounding environment beyond the boundary, the calculation of the dynamic current rating or a running simulation can be achieved on a longer-time scale. The current rating model based on the self-adaption is known as DCR-II model or cable proximity model.



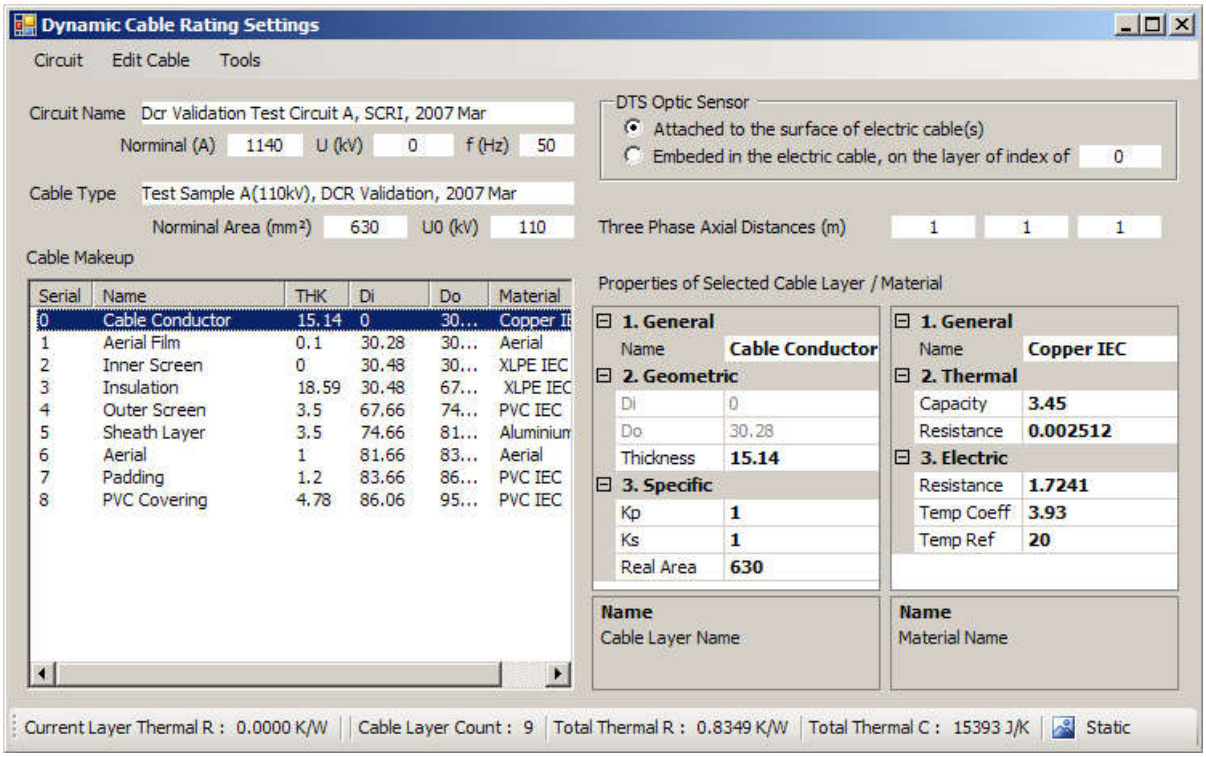
Overview of DCR I & DCR II

DCR-I Dynamic Current Rating Model

The DCR-I modeling parameters are the structure of cable circuits, including the geometric parameters and properties of the conductor and various layers. The followings are also needed:

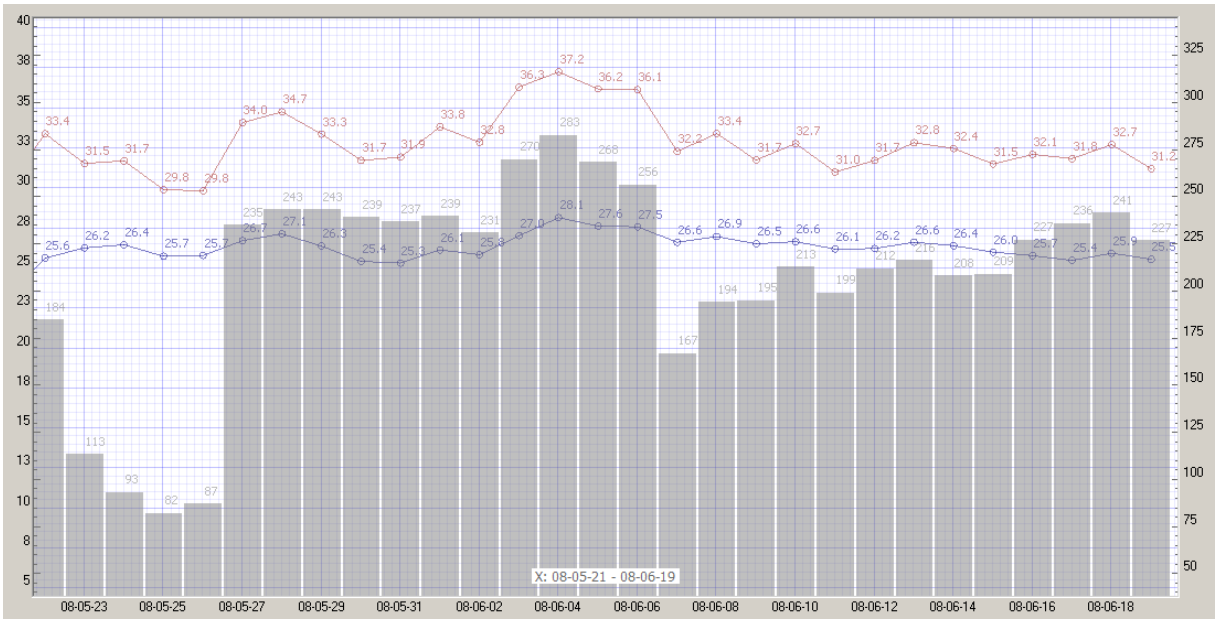
- Cross-sectional area of the conductor, resistance of materials and temperature coefficient of resistance; conductor skin and neighboring factor;
- The dielectric coefficient and dielectric loss angle of insulation materials;
- Sheath loss/shadow loss rate.

Neighboring factors and sheathing loss are affected by surrounding cables and should be offered by cable system designers or be calculated according to the installation situation. If the optical cable for temperature measurement is laid out on the cable surface, the contact resistance from the power cable surface to the optical cable and the conduction thermal resistance of the optical cable itself should also be included during modeling. The following is the input interface of the model parameters:



Screenshot of DCR I input parameters from Bandweaver RTTR

The input variables of DCR-I model are: real-time current and cable surface temperature detected by the real-time optical fiber for temperature measurement. Its internal state is the temperature field from the cable conductor to the boundary. The value of the boundary point is the temperature value of the optical cable for temperature measurement detected by DTS.



Comparison of fiber temperature, calculated conductor temperature and load

The graph above depicts the output DCR-I. bar chart shows the daily average current. The lower curve shows the highest cable surface temperatures detected by DTS. The upper curve is the maximum temperatures of the cable conductor calculated by DCR-I.

Currently there are at least two schemes for the implementation of DCR-I:

a) In the one-dimensional heat transfer partial differential equation under polar coordinates, using finite difference or finite element methods for the solution.
b) Numerical method for the solution of the cable thermal circuit model.

In order to arrive at an accurate solution, the grid or thermal circuit must be fine enough. Suppose that the largest temperature difference from the conductor to the cable surface is 50 º C, the number of grid elements would usually be required to be no less than 20 to ensure that the calculation error is less than + / -1.0 º C. IEC transient-state calculation provides modeling principles of the thermal circuit model and the simple thermal circuit model. These models usually take insulation and other cable layers as only one or two node units which makes it impossible to achieve accurate calibration of the thermal field. In several ELECTRA papers, the cable has been divided into more units. We should comply with the principles of decomposing large thermal resistance for the thermal circuit modeling, e.g. the insulation can be divided into more layers while the metal sheathing can be retained as one layer. The finite difference method can set the divided grid number freely, but it needs to address the intermittent coefficient problem, which is relatively cumbersome. Both of the two methods are required to handle the following issues:

1. Accurately allocating dielectric loss for each insulating layer and allocating sheath loss for the metal layer;
2. Guaranteeing the stability of calculation; if the explicit format is used, the time interval which ensures a stable refresh is very small and a longer time-span refresh cannot be performed. The Crank-Nicolson method is commonly used to ensure that calculations in various refresh cycles are stable.

Taking into account the computer precision and the computing power required for higher-order matrix processing, the maximum number of grid elements should not be over 50. In fact, the additional grid elements

do not provide significant contribution to the precision. A calculation example shows that in double precision, while the number of grid elements is respectively 30 and 100, the maximum deviation of their calculation is not more than 0.35 º C.

When the DCR-I model starts the calculation, an initial status (temperature field) needs to be given. In practical applications, the temperature inside the cable cannot be obtained. The temperature field can be estimated according to the latest load and the boundary temperature.

A well-designed DCR-I model should have the following:

- Accurately calculation for the conductor temperature;
- Stability after being refreshed at arbitrary time intervals;
- Stability at arbitrary initial status;
- Model functions for cables of different specifications (cross-sections and voltage ratings);
- Model function for different optical cable layout locations (e.g. within power cable protection layer or on surface of the cable).

VALIDATION TEST

As the conductor temperature cannot be detected in the cable for practical applications, it was necessary to perform related validation test to confirm the validity of DCR-I model.

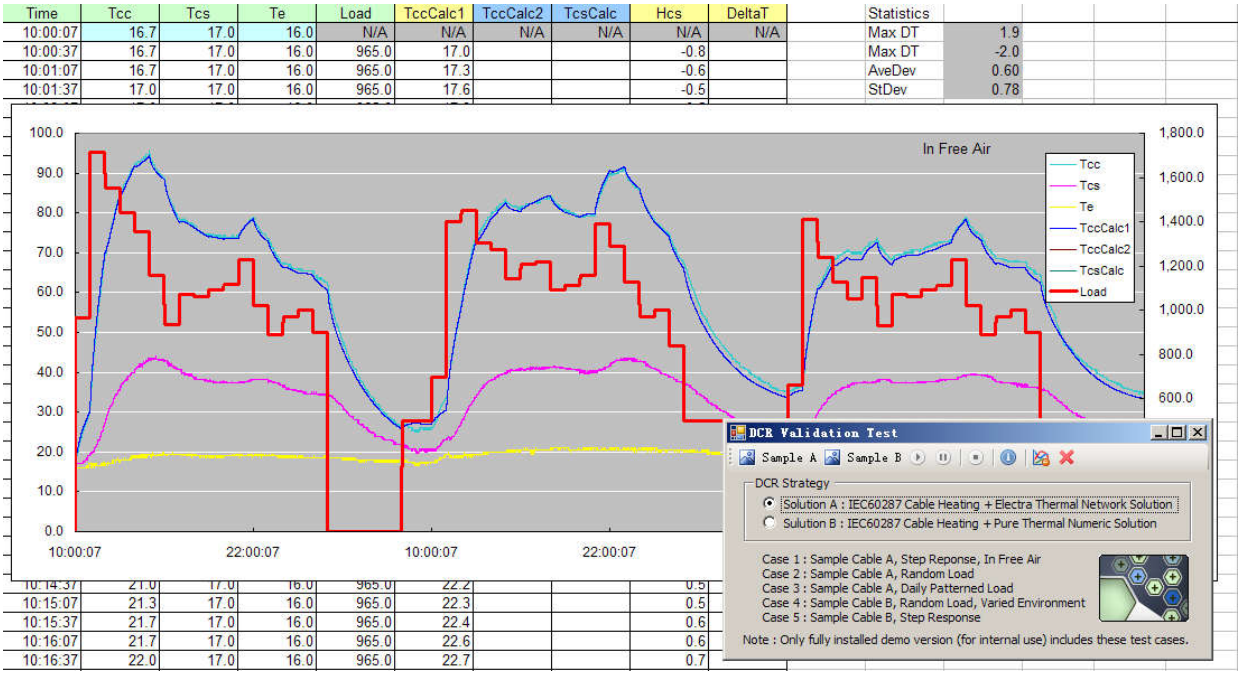
The basic facilities and conditions of the test are basically the same as for static testing of the cable. The test set up includes a test cable carrying high current, ability to measure the conductor temperature and surface temperature of the cable. The difference between the static test are:

- Current changes substantially throughout the testing;
- Recording currents, conductor temperatures and surface temperatures as standard data on a real-time basis;
- Conducted in different environmental conditions or even changing environments.

There are 2 possible methods for carrying out the test depending on the particular set up or client requirements. Bandweaver has carried out both methods.

1. The DCR-I model calculates the conductor temperature on a real-time basis.
2. DCR-I calculates the conductor temperature off-line in accordance with the current and surface temperature after the completion of the test. A complete scheme also includes DTS and optical cable. Thus the DCR-I needs to address the thermal resistance between the optical cable and the power cable surface in line with the actual application.

Below are some of the test results from two of the qualification tests that Bandweaver has carried out.



DCR-I Validation test results

In the above scenario, tests were carried out over a three-day operation in a cable tunnel environment. The load pattern was based on a specific daily load curve but included an element of randomness. The deviation of DCR-I model calculation was not more than + / -2.5 ° C from the measured values. The test was carried out at the SERC Institute, May 2007.

DCR-I Validation test set-up

In the above set up the monitoring system detected the temperature of the optical cable fixed on the cable surface through a DTS and the input current. The model calculated the conductor temperature on a real-time basis. The validation result: both in the air and in the simulation environment of flooding piping or forced ventilation were less than 2.0 °C from the measure values. The test was carried out by KEP & SEP in 2008

BOTTLENECK POINTS

The load capacity of the cable is typically limited by the maximum permitted temperature of the insulation materials. It is not determined by the overall heat-dissipating conditions of the cable, but generally by a few heat-dissipating points which are the most adverse (i.e. thermal bottlenecks). According to the heat source and thermal conductivity inside the cable, the law of bottleneck points can be derived mathematically. In the total length of a cable, if the time-variation constant of environmental conditions is much larger than the cable body heat conduction time constant (usually of an hourly magnitude), the crest of the surface temperature is also that of the conductor temperature which constitutes the static load bottleneck point of the cable. The theorem does not constrain the change of the current. Environmental conditions refer to object structures, properties and heat sources of the environment.

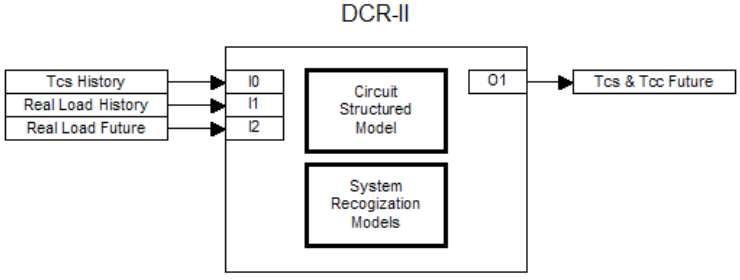
When the temperature gradient exists in the cable along the axial direction, at least a part of heat flows from the high temperature to the low temperature axially. But one-dimensional model assumes that all the heat is conducted in the radial direction. This means that if a mathematical model can accurately calculate the conductor temperature in the one-dimensional conditions, in the above circumstances, then the conductor temperature calculated at the bottleneck is slightly higher than the actual value. While on the contrary, the conductor temperature calculated at the location where the surface temperature is lower than its both sides is slightly lower than the actual value.

When environmental conditions change rapidly, the law of bottleneck points is not valid. Sudden heating of any point in the cable can make the surface temperature reach maximum, but the conductor temperature does not change yet. In reality, the similar situation usually exists, e.g. the cables at the joint wells and exposed cables may quickly be affected by the air temperature or sunshine change. In this case, the law of the bottleneck under weak conditions is still valid: the conductor temperature calculated continuously by the highest surface temperature of the full-length cable is not less than the actual highest conductor temperature of the full-length cable. At that time, the crest of cable conductor temperature is not necessarily the highest surface temperature.

DCR-II DYNAMIC CURRENT RATING MODEL

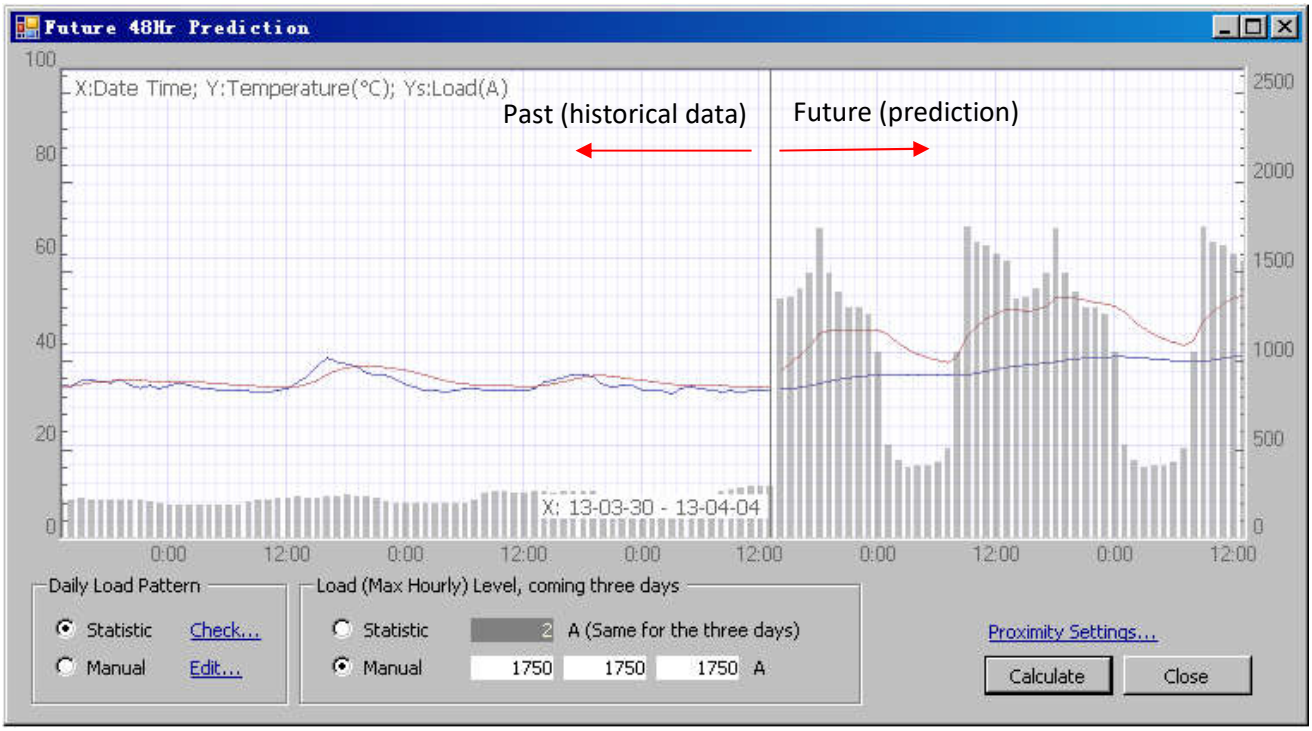
The inputs for the DCR-II model are:

- Historical data of the load current
- Historical data of the surface temperature
- Future load prediction



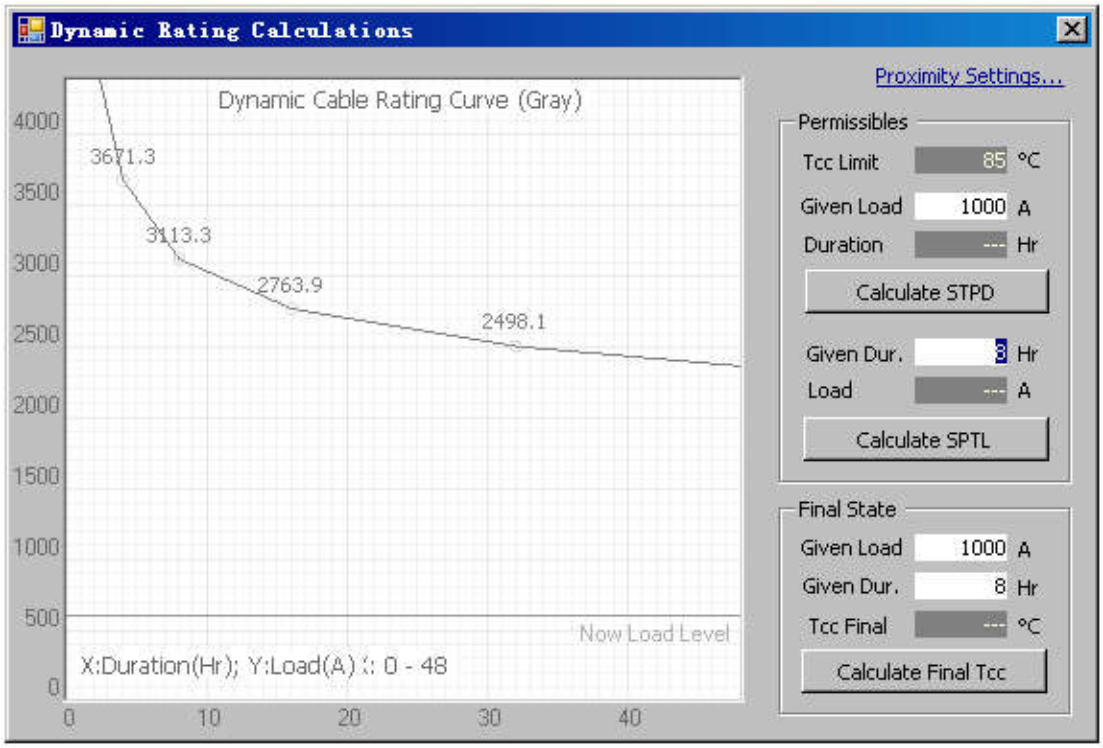
DCR-II model structure

The output is the curve of the future load current and surface temperature. The output of DCR-II also includes the function curve of future current ratings within a sustainable timeframe.



DCR-II – 48 hour prediction results

The above data set shows the output of the DCR-II simulation calculation. The vertical line in the middle represent the "present" time. On the left is the historical DCR-I data for the past four days. The bar charts represents the average current. The lower curve represents the highest cable surface temperature detected by DTS, and the upper curve shows the highest cable conductor temperature calculated by DCR-I. On the right of the line, the bars represent the predicted current for the next three days set by users (in this case a significant increase). The lower and upper curves respectively represent the highest temperature of the cable surface and the highest temperature of the cable conductor as predicted by the DCR-II model.



DCR-II – Functional curve of current rating vs time

In the above screenshot, you can see the RTTR's additional functionality whereby the user can calculate the Short Term Permissible Load (STPL) which is based on a specified duration or the Short Term Permissible Duration (STPD) which is based on a maximum load. This gives the user maximum flexibility to make quick calculations in an emergency rating situation.

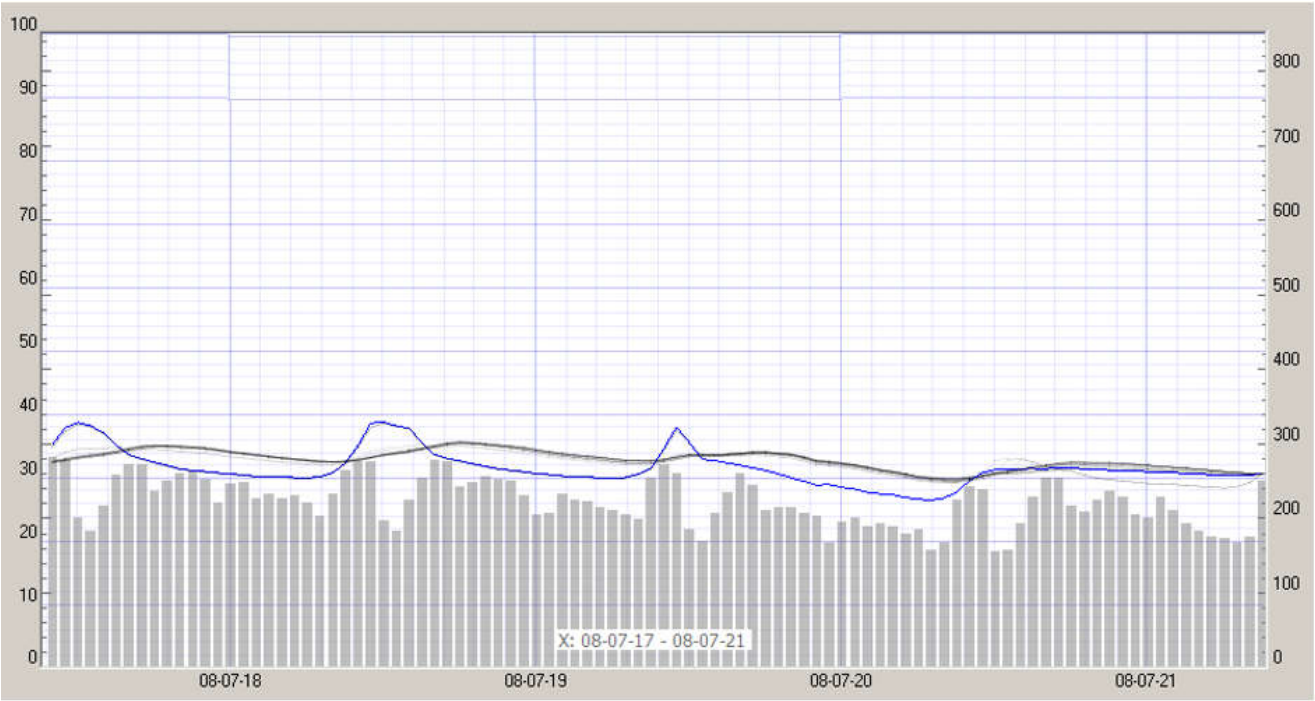
In fact, DCR-I can provide accurate DCR calculation for durations of less than 15 minutes. For longer duration, conditions of the surroundings or proximity of the cable need to be considered. The DCR-II algorithm includes several types of sub-models to describe cable proximity conditions including: air convection, conduction and IEC60287 T4. The convection model applies to tunnel cable or other cables in internal air environments, and the conduction model applies to piping and direct burial cables. DCR-II can begin working with only knowing the sub-model type and with limited property parameters. It can then calculate present temperature state of the model based on recent load temperature response behaviors (this is known as self-adaption).

In fact, the DCR-II simulation and current rating calculation are based on such an assumption. The boundary temperature of the environment near the cable does not change for a significant period of time (typically 12-48 hours). The time span of DCR-II calculation is usually designed to be less than 24 hours and for the completion of historical data calculation required by self-adaption should be at least the last 72 hours.

In comparison with DCR-I, there are more uncertainties with the DCR-II model. It incorporates environmental properties like soil thermal resistance and capacity which are entered as static values but may be uncertain or fluctuate. Under this situation, conservative values should be used to trade off the risk.

DYNAMIC BOTTLENECK POINTS

In practical situations, the location of the cable bottleneck point is not fixed and sometimes can change very fast, for example, cable near cable wells are vulnerable to the atmosphere and becomes the bottleneck point in the daytime while at night the bottleneck point shifts to other locations (this is similar to road crossings..). If we do not distinguish these bottleneck points, environmental information will be mixed together and there will be errors in the DCR-II model. Bandweaver has developed an algorithm (Bn24), which dynamically tracks the multiple cable bottleneck points. Since the movement of the bottleneck point is closely related to a similar timetable every day, the algorithm 24 finds the current bottleneck points collection per hour each day and monitors at similar times on the subsequent days.

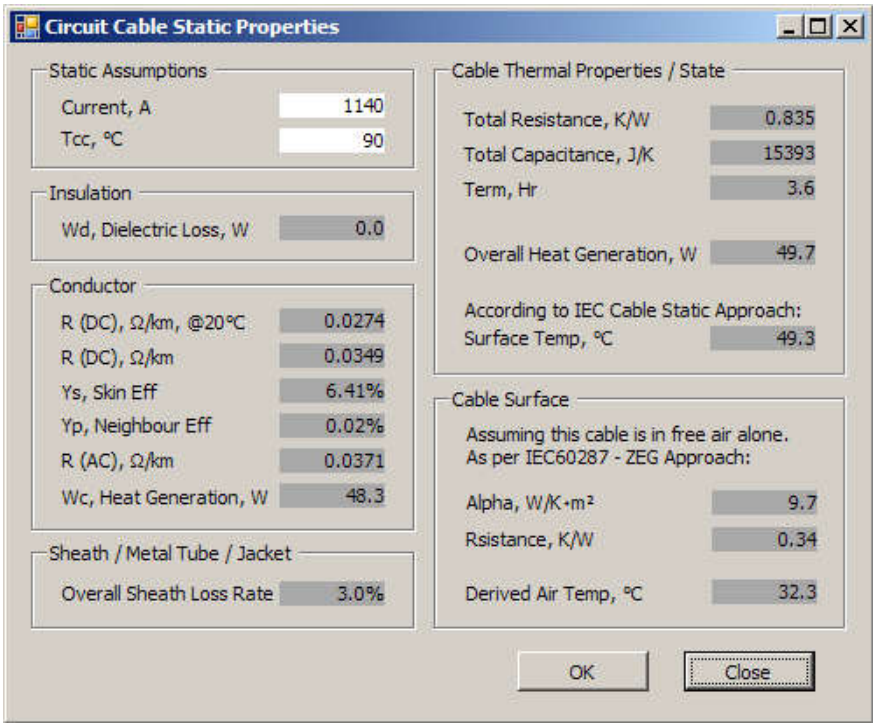


Bn24 Dynamic Bottleneck Points Tracking Results Interface

In the above screenshot, it shows 96 hours of data. The bars show the average current values. The traces show the cable surface temperature history of bottleneck points corresponding to each hour. One of the traces shows specifically for the point in the cable well which you can see is not the consistent bottleneck. Data is from SEP Substation 1130 Line.

CABLE SURFACE TEMPERATURE RATING METHODOLOGY

Taking the surface or protection layer of the cable as the boundary, a (partial) static model can also be set up. Similar to DCR-I, this model does not contain uncertain factors. For the rated state, the cable surface temperature is also determinate. While the cable system load designer calculates the rated load in accordance with IEC60287, the designer also obtains the cable surface temperature in the rated state. It clearly follows that as long as the load current and the cable surface temperature do not exceed the rated value, the cable conductor temperature is guaranteed not to surpass its rated value, and the cable remains in the safe status.



Screen shot from SEP Substation 1130

The data above is take from SEP substation 12130. The data shows that the rated cable surface temperature is 49.3°C

Thus a static method of the cable load safety level monitoring is obtained. The premise is then that by ensuring the highest surface temperature throughout the whole cable does not exceed this value then the load current will not exceed the rated current. If during monitoring the highest surface temperature exceeds the rated value, we may regard it as overload and issue an overload alarm. This method is very simple and feasible based on DTS, as long as the highest temperature alarm value of the DTS real-time detection is set to be the rated cable surface temperature. It should be noted that the fire alarm temperature value at the international standard at present is 58ºC. If the rated cable surface temperature is greater than this value, the maximum temperature alarm value can still be set as the rated cable surface temperature due to the support of temperature rise and other intelligent alarm modes.

SUMMARY AND CONCLUSIONS

Distributed Temperature Sensors and Real Time Thermal Rating technologies are increasingly becoming standard in the management of power cable systems. They provide great potential to safely provide additional capacity over and above the conservative static calculations that are prevalent in the industry today. It is our belief that they will continue to grow and form an essential tool for the Smart Grid of today and tomorrow.

ABOUT BANDWEAVER TECHNOLOGIES

Bandweaver has been providing advanced fiber optic monitoring sensors and integrated technologies since 2002. Their technology portfolio covers a wide range of sensors including distributed Temperature Sensors (DTS) and Distributed Acoustic Sensors (DAS) and integrated smart intelligent software solutions. Within the Power and Utilities sectors, Bandweaver's distributed fiber optic acoustic and temperature sensing systems provide the operator with real time critical information on their network. This assists in reducing planned and unplanned maintenance and avoiding catastrophic failure along with managing risk effectively.

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