CONTINUOUS SAFEGUARDING OF RATING ACCURACY

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ABSTRACT

This paper presents a new approach for continuous safeguarding of the accuracy of real-time thermal rating (RTTR) predictions of power cables. Comparisons of RTTR predictions with (slow) finite element simulations are suited for an offline validation of thermal models before they are deployed in the field. However, the accuracy of RTTR predictions does not only depend on the accuracy of the models but also on variations of ambient parameters and other external influences such as heat sources. Therefore, an on-site real-time evaluation of the rating accuracy is required for safeguarding the quality of RTTR predictions and finally for relying on those predictions in the safe operation of power cables.

INTRODUCTION

By using regenerative energy sources, more and stronger fluctuating electrical power has to be transmitted by the grid. An efficient use of the grid requires a safe operation of power cables at high and strongly varying load conditions. Real-time temperature monitoring solutions become essential for a safe operation of power cables under such conditions. The monitoring solution has to ensure that the maximum permitted temperature of the conductor must not been exceeded at any location along the cable route. Distributed temperature sensing (DTS) using optical fibres of the cables is commonly used for recording temperature profiles of power cable installations. Optical fibre may be incorporated in the screen or attached to the sheath of a power cable. RTTR software is used for calculating conductor temperatures and for predicting future temperature, time and load conditions. In order to use the rating results in the operation of power cables, it is essential to have some reliable information on the accuracy of the RTTR results. We propose a solution for continuous safeguarding the accuracy of RTTR predictions for conductor temperatures and demonstrate the performance of the RTTR engine for situations that are not included in the thermal models of the power cable installation.

REAL-TIME THERMAL RATING

RTTR software packages mainly use thermal models of power cables according to the standard IEC 60287 [1], load data and temperature data from DTS for calculating conductor temperatures and ampacity / temperature / time predictions. The thermal models of the power cable installations are based on equivalent circuit diagrams. In those diagrams, the thermal properties are described in an analogy to electric circuits: temperature (T) corresponds to voltage, heat losses (W) to current sources, thermal resistances (R) to electrical resistances and heat capacitances (C) to electrical capacitances. An example is shown in Figure 1.

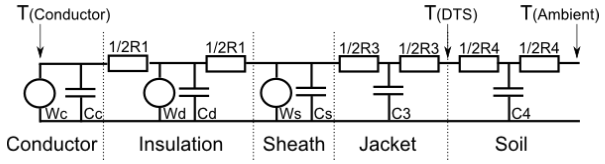

Figure 1: Equivalent circuit of a buried power cable.

The full thermal model has to consider the power cable design, cable formation, operating frequency, thermal properties of the materials inside and outside the cable, ambient temperature and the position of the DTS optical fiber. DTS temperature and current load histories are also required for RTTR calculations. Measurement of the DTS temperature separates the thermal model into two parts: inside (between fibre and conductor) and outside the DTS optical fibre position. Only the inside part needs to be considered in conductor temperature calculations, whereas the full model is required for predictions.
If the optical fibre is inside the screen or attached to the power cable, conductor temperature calculations use precisely known thermal properties of the cable formation and precise measurement data. Numerical simulations and on-site tests have proven that those conductor temperature calculations are highly accurate. [2], [3]
Ambient parameters such as ambient temperature and thermal resistivity of soil are required for predictions since future DTS temperatures are unknown. Ambient parameters may vary considerably with the seasons. It is obvious that current ambient parameters need to be known for accurate predictions. External heat sources and other parameters not considered in the thermal models may also affect the accuracy of conductor temperature predictions.

CALCULATION OF AMBIENT PARAMETERS

We developed an algorithm for determining ambient parameters such as thermal resistivity of soil and ambient temperature in real-time from current load and DTS temperature histories. A seven day evaluation period of current load and DTS temperature data was used for calculating the ambient parameters. Some load variations within the seven day period are required for determining both parameters simultaneously.

We validated the accuracy of these calculations for a wide variety of installation schemes and load scenarios by comparison with finite-element-method (FEM) calculations. Nevertheless, a real-time accuracy evaluation of RTTR ratings based on the estimated ambient parameters is important for operators to gain trust in the rating results.

RATING ACCURACY

Our approach for evaluating the accuracy of RTTR predictions is based on the comparison of two differently calculated conductor temperatures, schematically shown in Figure 2. As a reference we use the very accurate conductor temperature calculated from measured load and measured temperature, which we compare against a predicted conductor temperature starting at a defined time in the past using only the measured load.

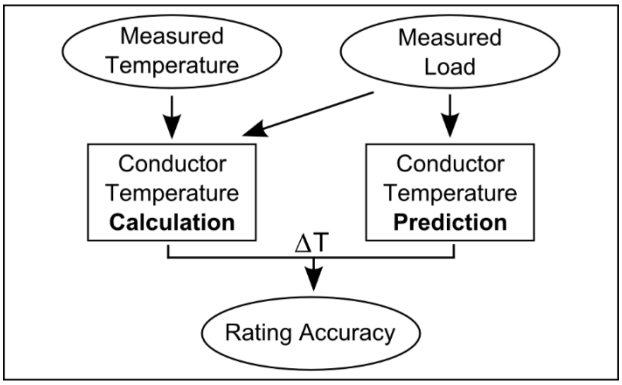

Figure 2: Rating accuracy concept.

An RTTR engine with the capability to calculate predictions for non-constant load was used in rating accuracy calculations. All those calculations can be performed in real-time, every 10 minutes and for a number of automatically selected critical locations. User-defined pre-alarm and alarm thresholds may be used for automatic triggering of actions in case of insufficient rating accuracy. The real-time capability of the rating accuracy calculations enables to monitor the quality of the RTTR in the field. The accuracy of the rating results may be affected by potential weaknesses of the RTTR engine, differences between real installations and thermal models, fast variation of ambient parameters as well as external heat sources not considered in the thermal models. In any of those cases, the real-time rating accuracy calculation can detect the insufficient accuracy of the RTTR predictions. The resulting pre-alarms or alarms can be transmitted to the SCADA system.

NUMERICAL SIMULATIONS

FEM simulations have been performed using COMSOL Multiphysics®. The rating accuracy results presented here were calculated for a flat formation of single core power cables buried 1m deep in the soil (Figure 3). For the ease of the discussion we will for now only consider the centre cable of the installation, while a real rating accuracy monitoring needs to consider all cables.

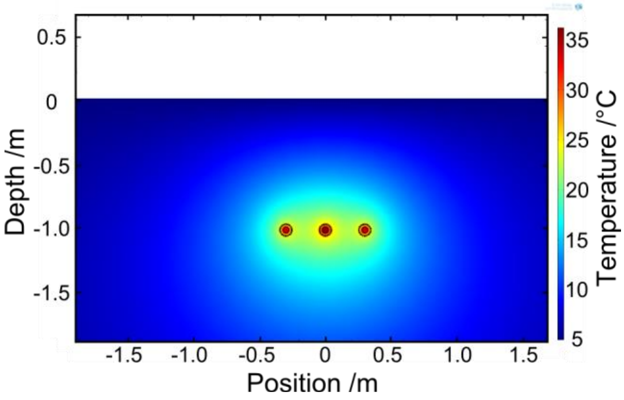

Figure 3: Temperature distribution around power cables in flat formation calculated by a FEM simulation.

Rating accuracies shown here refer to conductor temperature predictions over 24 hours using a typical load profile as shown in Figure 4.[4] The load profile was scaled so that the maximum difference between conductor and ambient temperatures is about 30°C. The daily variation of conductor temperatures by about 15°C resulted from using the load profile shown in Figure 4. It should be mentioned that the engine has the capability to calculate rating accuracies for any reasonable prediction time, for any load profile and for a wide variety of power cable installation schemes.

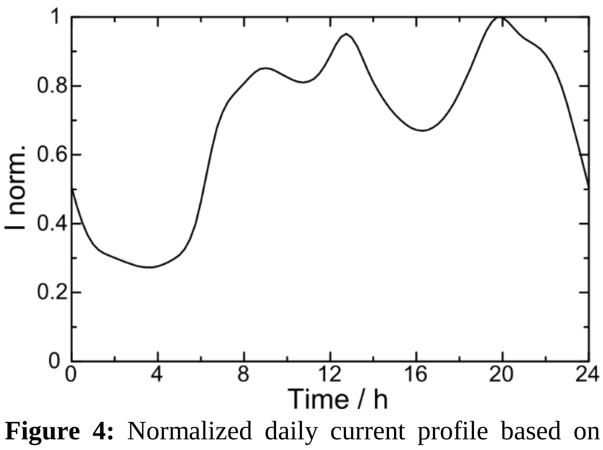

Figure 4: Normalized daily current profile based on a standard load profile for Germany (H0).

RATING ACCURACY RESULTS

Constant Ambient Parameters

A first simulation was performed under the assumption that the ambient parameters are constant and that there are no external heat sources. The initial conductor temperature was the same as the ambient temperature (5°C). The predictions started after 7 days when the first calculation of ambient parameters (based on data from that 7 days period) had been completed. The time axis of Figure 5 starts at day -7 in order to shift the point of origin to the starting time of the predictions.

After applying the load at day -7, the conductor temperature increased over time and showed a pattern corresponding to the daily load cycle (Figure 5). Due to the thermal inertia of the soil, the increase of the conductor temperature was quite slow and not fully completed even after about one month.

The rating accuracy results are shown in Figure 6. For better visualisation of the general trend, only the maximum value for each day is shown in the figure. The figure shows also some reasonable pre-alarm and alarm thresholds of +/-2K and +/-4K.

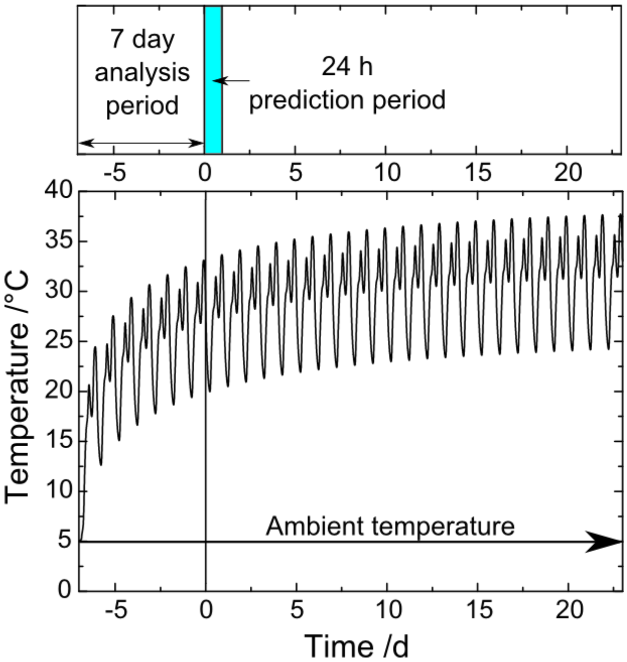

Figure 5: Conductor temperature history for constant ambient temperature and without external heat sources.

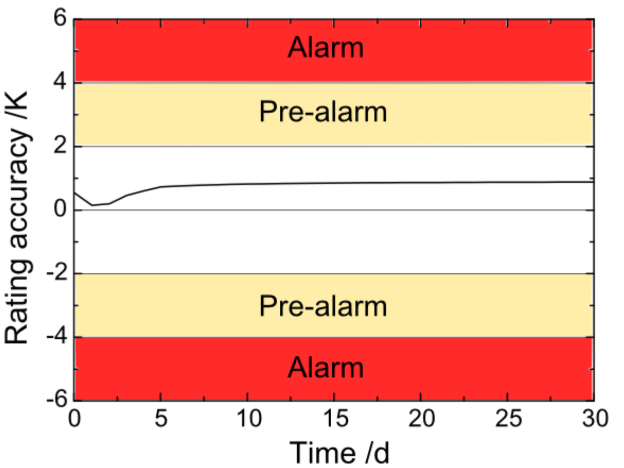

Figure 6: Rating accuracy history for constant ambient conditions. Pre-alarm and alarm levels are highlighted.

The rating accuracy shows some small variation within the first days and finally remains constant at about 1K. Pre-alarm and alarm thresholds are not exceeded. This confirms the stability and accuracy of the 24 hour predictions on the conductor temperature. A rating accuracy result of 1K means that the predicted conductor temperature is 1K higher than the directly calculated one. The reason for the slightly higher prediction results is due to an imperfect initialization of the thermal model. Further improvements of the initialization are identified, so that future results are expected to be even better. Further improved rating accuracy results are expected for a future implementation using longer evaluation period and/or more appropriate initial values.

Effect of Changing Ambient Temperature

Ambient temperatures vary with the seasons. In order to analyse the effect of changing ambient temperatures on the rating accuracy, a simulation was performed under the assumption that the ambient temperature starts to increase on day 0 with a rate of about 0.7 K/day (Figure 7), which is already a big change if compared to seasonal changes in the typical laying depth of power cables. As expected, the trend of the conductor temperatures approaches the same slope after a few days.

The worst case rating result is approximately -1.5K about two weeks after starting the change of ambient temperatures (Figure 8). It never exceeds the pre-alarm or alarm thresholds and finally approaches a value close to 0K. The result shows that this strong change of ambient temperature has only a little effect on the rating accuracy, and the operator of the power cable can fully rely on the predictions even if the ambient temperature changes.

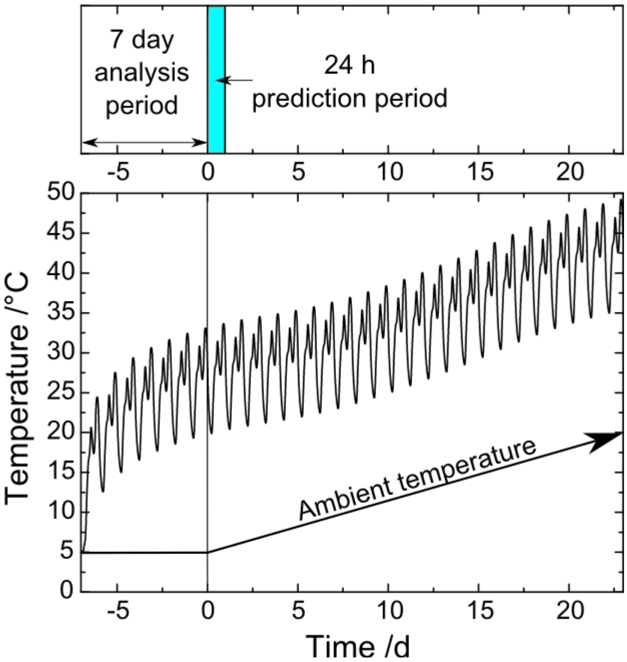

Figure 7: Conductor temperature history for rising ambient temperature.

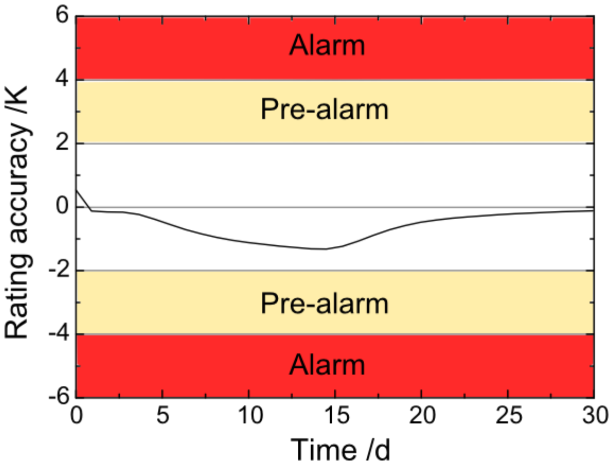

Figure 8: Rating Accuracy history for rising ambient temperature.

Effect of External Heat Sources

Heat sources not considered in the thermal model such as steam pipes or other power cables can seriously change the thermal environment of a buried power cable. We investigated the effect of such a heat source on the rating accuracy by adding a heat source with a power of 100 W/m in a distance of 1m to the power cable formation. FEM simulations showed that the temperature distribution in the soil around the power cables can be strongly changed by adding that heat source (Figure 9). As it can be seen from Figure 9 the cables might be differently affected, which requires to check the rating accuracy for all cables for safe operation of the circuit.
For evaluating the rating accuracy, the heat source was not operated permanently, but started its operation after running the rating accuracy calculation for 2 days (Figure 10).

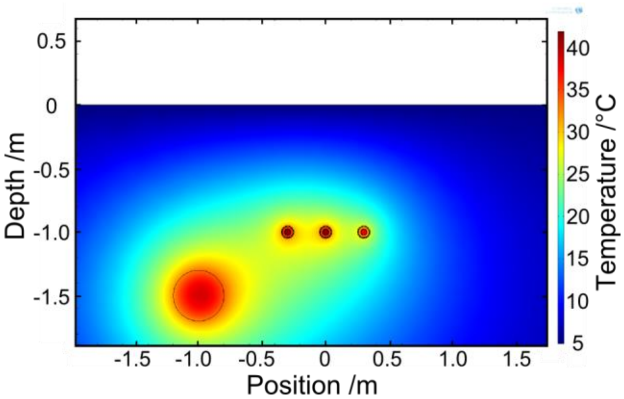

Figure 9: FEM temperature distribution in a power cable installation with a neighbouring heat source.

Because of the extra heat source, the conductor temperature reached more than 60°C after about three weeks. The rating accuracy history (Figure 11) shows that the rating accuracy goes down to about -5K within a few days after starting the operation of the heat source.

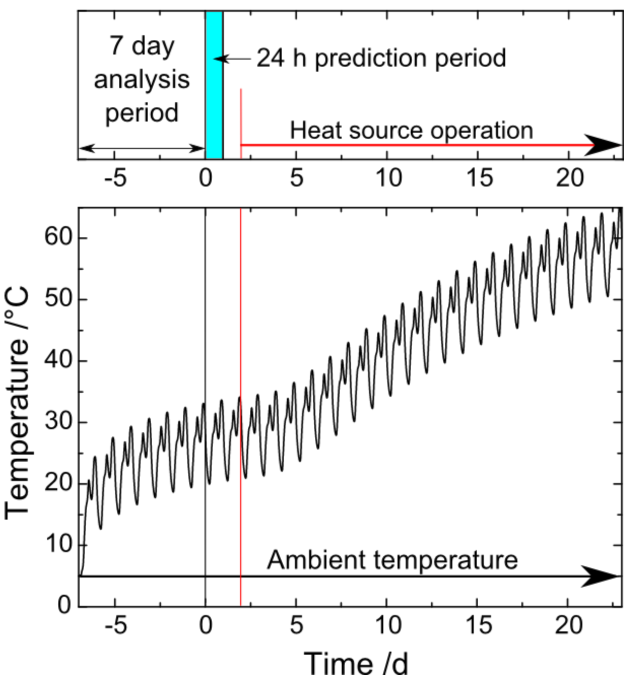

Figure 10: Conductor temperature history for constant ambient temperature and non-constant heating of soil by a heat source.

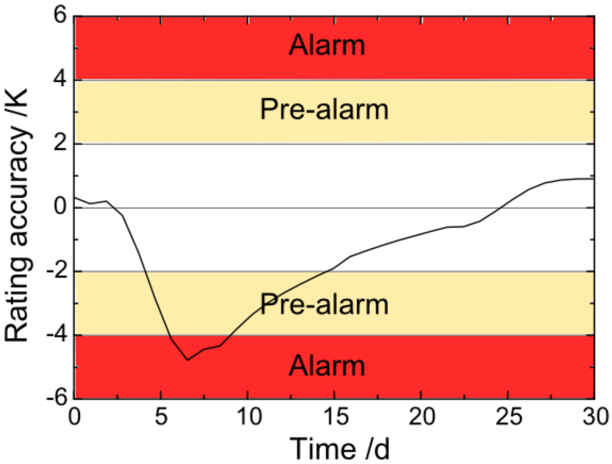

Figure 11: 24h Rating Accuracy history for constant ambient temperature and non-constant heating of soil by a heat source.

However, the rating accuracy recovers within about two weeks and finally approaches normal values within +/-1K. This result shows that starting to operate a strong heat source in the vicinity of a power cable may seriously affect the rating accuracy. It also shows that the algorithm for calculating the ambient parameters can cover this situation after some time and accurate RTTR predictions are obtained even if an unknown strong heat source is permanently operated close to the power cable installation. The period where the rating accuracy is without the desired limits is precisely known to the operator because pre-alarms and/or alarms are triggered.

CONCLUSIONS

The presented continuous, real-time evaluation of rating accuracy enables a real-time safeguarding of the accuracy of RTTR conductor temperature predictions. The effect of changing ambient temperatures and external heat sources on the rating accuracy were analysed. With the RTTR engine used for the predictions, changing ambient temperatures did not seriously affect the rating accuracy, whereas starting the operation of a strong heat source in the vicinity of a power cable temporarily led to an insufficient rating accuracy. The algorithm for calculating the ambient parameters has the capability to adequately consider changes of ambient temperatures and effects of constantly operated heat sources that are not included in the thermal model of the power cable installation.

The proposed continuous safeguarding of rating accuracy may become an important tool for generating stronger confidence in RTTR predictions on conductor temperatures of power cable installations.

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