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ADAPTIVE MONITORING PROGRAM FOR DYNAMIC THERMAL RATING OF POWER CABLES

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ABSTRACT

Real-time thermal rating of cables has the fundamental problem that not all parameters of the cables and the trench, e.g. material properties and geometry, are well-known along the cable route and, moreover, that they may change unnoticed and undefined along the route and may vary by time.

An RTTR-system has been developed, which is able to compute predictions of heating trends and/or of load reserves respectively, using measured temperatures provided by customary monitoring systems. Critical system conditions can be identified at an early stage and alarm messages can be sent to the operator.

Parameter adaptation is realised by means of an evolutionary algorithm, the continuous execution of which has been proved to be accurate and extremely robust.

Tests have been performed for extreme situations, e.g. for neighboured district heating pipes and cables, which are not initialised in the thermal model, as well as for a consecutive drying-out of the soil. Situations such as extremely bad initial values are analysed and adapted in the model. Forecast errors normally remain below a limit of 1 K.

KEYWORDS

Real Time Thermal Rating, Power Cables, Temperature, Monitoring, Parameter, Adaptation, Prediction

1. INTRODUCTION

Temperature measuring systems for power cables with integrated optical fibres are a well established state of technology. During operation these systems provide information on the present sheath temperatures along a cable route up to approx. 20 km length within an uncertainty of about ± 1 K and a spatial resolution of ± 1 m.

Real time thermal rating (RTTR) means the interpretation of the incoming measured data of the sheath temperature with respect to typical questions as:

- What are the actual conductor temperatures, and where are the hot-spots?
- How long can the present current be transmitted before the condition becomes critical?
- Retaining the present load, which conductor tempera-ture will arise at the end of a given time interval?

Theoretically, questions like these could be answered by means of well-approved thermal models as proposed by International Electrical Commission (IEC) [9, 10]. However, there are some fundamental problems applying the equations given by the IEC to real cable routes: not all of the construction parameters of cables are well-known along the cable route. They may change extremely along the route or they may depend on time. Most of the time-dependent changes are simply not noticeable by the operator, for example the drying-out of the adjacent soil or the subsequent installation of parallel or crossing cables or district heating systems are not noticed.

In a study [1] sponsored by the Deutsche Forschungs-gemeinschaft (DFG), the fundamentals for an RTTR-system have been developed. This RTTR-system is able to compute predictions of heating trends and/or of load reserves respectively, using measured temperatures and current loads provided by a customary monitoring system. Uncertainties and variations of the cable route's parameters are considered by means of a continuous parameter adaptation. Critical system conditions can be identified at an early stage and transferred to adequate alerts for the operator.

Before the RTTR is operated, the parameters of the thermal model are identified and initialised as exact as possible by means of a simulation tool using the Finite Element Method (FEM) [2] or, alternatively, by the calculation rules of IEC-publ. 60287 and 853-2. In certain time intervals during operation, all model parameters are adapted to the incoming informations, so that predictions can be made on the base of a well-adapted thermal model. Special temperature-dependencies, i.e. of the cable losses, can be modelled by specific parametric elements, which are also submitted to the optimisation procedure.

Parameter adaptation is done by means of an evolutionary algorithm. The continuous optimisation by this genetic algorithm has been proved to be accurate and extremely robust [1].

Tests have been performed for extreme situations, e.g. for neighboured district heating pipes and cables, which are not initialised in the thermal model, as well as for a consecutive drying-out of the soil. Situations like bad initialisations are as well analysed and adapted by the model, e.g. by initial values deviating by 50 % or more from the actual parameters.

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2. DEVELOPMENT OF A CALCULATION MODULE

Today's power cables normally have copper screens, where tubes with optical fibres can be integrated. Temperature variations causes local changes in the optical density which enable temperature measurements with spatial resolution [4].

As the optical fibres are placed between the stranded screen wires, they measure the screen's temperature slightly changing along the circumference of the cable core. Averaging provides the arithmetic mean value of the temperature.

This results in the possibility of sampling screen temperature along the entire cables in rather short time intervals of e.g. 15-minutes periods. These measured temperature values are used in the monitoring system.

A suitable computation model is derivated on the physical qualities of typical laying arrangements of power cables. Each layer within the cable construction as well as in the cable environment has specific thermal qualities which can be approximately described by means of thermal resistances and thermal capacities (T- and C-elements).

3. T-C-NETWORK AS THERMAL EQUIVALENT CIRCUIT

As it is recommended in corresponding IEC-Publications [9, 10], the examined arrangement of cables is modelled by an equivalent ladder network (ELN). This thermal equivalent circuit contains T- and C-elements, which represent the thermal resistances and thermal capacities in specific areas. Such ELN are accepted and approved in the cable technique, where usually linearity and well defined elements are the basis. The model must be constructed in a very general way to take into account all possible configurations. For example:

- external thermal sources such as district heating pipes,
- parallel or crossing cables or
- temperature dependent thermal resistances of air layers (tunnel, duct, pipe).

The realised RTTR makes use of such a model. The thermal parameters for a certain cable environment can be modified according to the comparison of measurement and simulation. After adaptation the thermal equivalent circuit does not necessarily show exactly the structure of the IEC-model, but consists of an optimised number of elements, which will be explained in the following.

4. REQUIRED NUMBER OF ELEMENTS IN THE ELN

T-C-ELN of different complexities have been examined to find out whether and how well the temperature behaviour of arrangements can be simulated. A powerful FEM-program [2], which is able to take linear as well as non-linear thermal and electromagnetic effects into account, e.g. the time-dependent drying-out of soil, was used to simulate cable systems as close to reality as possible. In this basic study this FEM-program was used to provide the fictitious "measurement data".

The parameters of the ELN are adapted in a training phase, where simulation results and measurement results are brought into agreement. This is done by means of operating tools on the basis of evolution strategies which adapt the ELN elements to FEM-requirements as much as possible.

For a first step analysis a simple T-C-network with only three T-C-elements was chosen as an ELN. But nevertheless, the measurement and extrapolated simulation are already in a good agreement within a relative short period of a few hours. If this period increases, the limitations of such a simple ELN become quickly evident.

To improve the model a step by step extension of the ELN by further T-C-elements was done. As presumed, each extension with additional T-C-elements leads to an improved correspondence between nominal and actual values, i.e. up to seven T-C elements.

A further enlargement of the number of T-C-elements did not show any further improvements.

5. TEMPERATURE-DEPENDENT PARAMETERS

The ELN can be further improved by additional modelling of the specific characteristics of the cables. To consider specific temperature dependencies, as they are related to the current losses or to the non-linear thermal resistances of air layers e.g. in tunnel and pipe arrangements, it is essential to integrate additional parametric 2-port-networks within the ELN.

Fig.1 shows such an ELN which takes the temperature-dependent current losses into account. It subdivides into an electric part and a thermal part. In the same way further temperature dependencies can be taken into account if necessary.

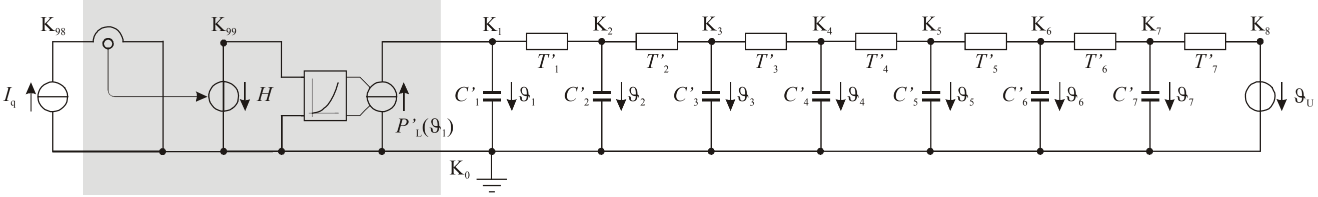

Figure 1: ELN as T-C-ladder network with 7 T-C-Elements with parametric consideration of the temperature dependency of the conductor resistance (grey highlighted); the sensor is located in knot K2.

Taking into account the temperature dependent conductor resistance, the ELN with 7 T-C-elements according to Fig.1 is proved to be optimal for the representation of most different cable systems. Therefore it is used in the further examinations.

6. OPTIMISATION

The identification of the parameters free of choice of the thermal ELN is done by optimisation, which minimises the deviation of the temperature pattern simulated by the network model from the measured (FEM-simulated) temperature values. For optimisation a tool called SPICEOPT, which determines model parameters on the basis of the network analysis program SPICE [7], is used.

The quality of the approximation is measured by a quality measure *Q* which calculates the sum of the squared temperature differences between calculated and measured temperatures.

For the choice of a suitable optimisation algorithm the knowledge of the basic structure of the problem according to Fig.1 is necessary. Although the ELN contains 17 free parameters, here, the progression of the quality measure *Q* is calculated in a searching area, which is two dimensional only, so that the result can be visualised. In this example the other 15 free parameters are regarded as constants, after an estimation within a complete (17-parameter) optimisation.

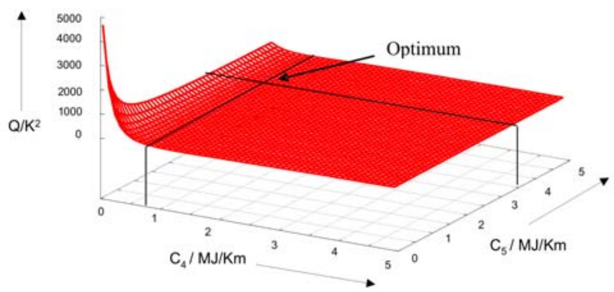

Figure 2: Progression of the quality measure *Q* in a two-dimensional searching area (C_4, C_5).

As can be seen in Fig.2, there are only very slight gradients in the interesting area close to the optimum ($C_4 \approx 0.7$ MK/Km, $C_5 \approx 3.5$ MK/Km). Detailed analysis shows furthermore that small local minima exist. Applying a simple gradient method is not suitable to this problem.

Because of these local minima an optimisation algorithm using evolutionary strategies has been implemented. N stochastic vectors are chosen within a certain searching area, for which the quality measure *Q* is determined. If one of the stochastically searched successors is better than the starting values, the best successor will become the new set of values for the next generation. At the same time the searching radius is increased by a certain factor *1/r*. If none of the successors is better than the starting value, then the searching area will be reduced by the factor *r*. This procedure is repeated as long as the searching radius does not undermine a certain threshold value. The algorithm is implemented in SPICEOPT, whereas the parameters

- number of successor per iteration step *N*,
- start-searching area r_{start}
- reduction factor for the searching radius *r*
- threshold searching area r_{min}

are adjustable and are adapted during the optimisation process. The optimisation criterias are the quality measure *Q* at the end of the optimisation as well as the calculation time.

For each of the parameters to be optimised a maximum search interval can be fixed. This eliminates physical implausible solutions (e.g. negative resistor values) and the process of optimisation in the adaptation phase is speeded up by restricting the search area to the same area of the previous optimum.

7. DRYING-OUT OF SOIL AND EXTERNAL HEAT SOURCES

As a typical and foremost critical example, a drying-out soil with a simultaneously existing external heat source is being chosen to test the rating program. Since measurements were not available, the “real” temperature values were obtained by FEM computations.

The phenomenon of out-drying soil may be caused by the heating of the cable system itself but also by the influences of the cable’s environment. Dried out soil shows a remarkable increase of the thermal resistivity of the soil whereas the heat capacity C’ decreases. Any other power cables in the surrounding of the cable system also warm up the environment and will have influence on the cable route. Such external cables are considered to be run by their own unknown load profiles so that the cable system being investigated is influenced by additional power flows in the soil layers. In the electrical equivalent circuit diagram this factor could be represented by means of additional current sources.

In addition other thermal sources, such as district heating pipes, could exist. Normally they are run with a constant temperature so that they could lead to an offset of the environment’s temperature. In the electrical equivalent circuit diagram this could be modelled by using an additional voltage source.

Additional current and voltage sources increase the complexity of the ELN and the number of the free parameters. This leads to a longer computation time. The ELN used within the RTTR-system does not need to contain such additional sources. Due to the periodic adaptation ability of the RTTR-system the model automatically considers the effects of the drying-out soil and external heat sources.

The combined influence of the drying-out soil with a coexisting external heat source on the temperature behaviour of the cable system is shown in Fig.3. Regarding the FEM-calculated example, the excitation takes place by a typical day-load-cycle starting at the beginning of the first day. At the beginning of the simulation the temperature of the cable system is the same as the ambient temperature (thermal initial condition). The calculation was done for a period of one month at a time step of 600 s.

In this example the external heat source is represented by an additional external cable system located at a distance of 0.3 m to the cable system being investigated and which is operated by its own, but for the RTTR-model unknown load cycle. This external heat source is switched-on at the same time, as the investigated cable.

A short time after starting up the external heat source the temperature already increases significantly compared to the cable route without external heat source. In the following the grey highlighted intervals in Fig.3 will be further discussed.

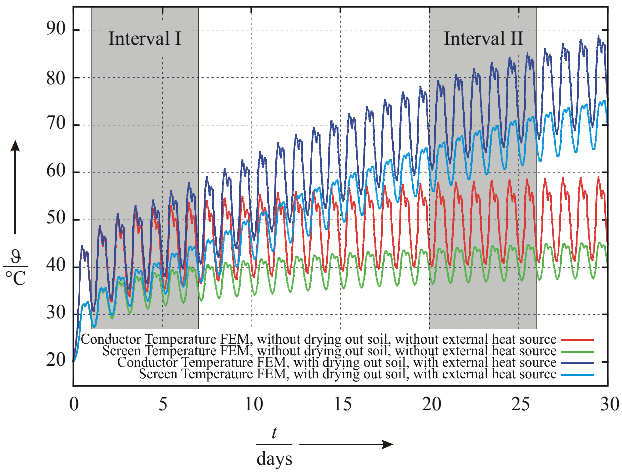

Figure 3: Screen and conductor temperature progression calculated using FEM with and without drying-out of soil and with and without external heat source.

With the FEM calculated temperatures in Fig.3 for an out-drying soil and an external heat source the ability of the ELN (Fig.1) to reproduce the thermal behaviour is analysed.

For this, the grey highlighted interval no. I in Fig.1 will be first analysed. The equivalent circuit diagram is adapted beginning with the 2nd day over a time frame of one day. During this process all elements C_i and T_i for i > 2 (i.e. outside the screen) as well as the initial conditions of all heat capacities are being optimised. After completion of the adaptation, a prediction period of five days is shown in Fig.4.

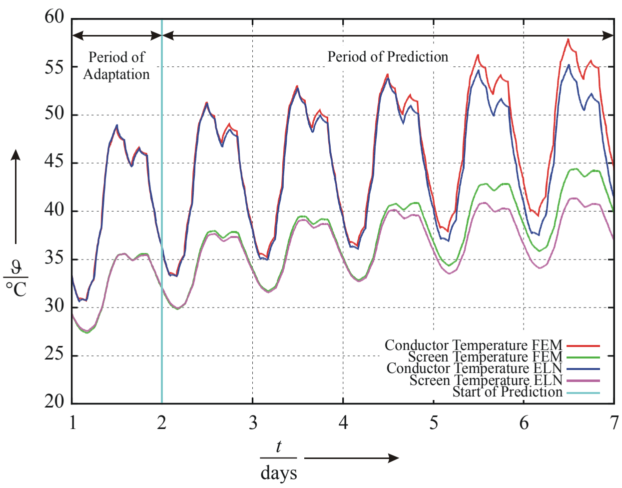

Figure 4: Comparison of Interval I in Fig.3:
Screen- and conductor temperature progression, calculated with FEM and ELN, with drying-out soil and an external heat source, adaptation after day 1, begin of prediction after day 2, deviation in the interval of prediction.

The result in Fig.4 shows an excellent correspondence of the temperature progression during adaptation (until the end of day no. 2). The curve after the second day shows how difficult it is to predict the external heat source. It results in the deviation of the curves beginning at the 3rd day.

A prediction over a short period of time is indeed possible even with the condition of drying-out soil and for unidentified external heat sources.

Most important for the RTTR-system is its ability to adapt the elements within the ELN following the real thermal processes in a proper way even if unforeseenable phenomena such as drying-out soil and external heat sources occur.

To test this critical aspect the calculation was repeated after 20 days (grey highlighted Interval II in Fig.3). During the operation from day no. 2 to day no. 20 a periodic adaptation of the equivalent circuit takes place. The last adaptation phase takes another day and is followed by a prediction over 5 days. The results are shown in Fig.5.

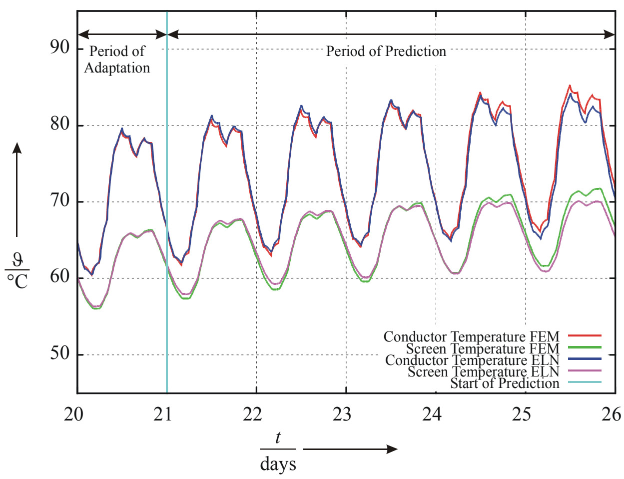

Figure 5: Comparison of Interval II in Fig.3
Screen and conductor temperature progression calculated with FEM and ELN with drying-out soil and an external heat source, adaptation after day no. 20, beginning of the prediction after day no. 21, and deviation in the area of the prediction.

Fig.5 shows that the simulation model can emulate the thermal behaviour even for the occurrence of drying-out soil and under the influence of an unknown external heat source (until the end of day no. 20). At the interval of prediction (beginning day no. 22) there is even a remarkable improvement in approximation quality compared to Fig.4. This is the result of the statistical uncertainty of the unknown external heat source. In general it can be assumed that from step to step the unknown behaviour of an external heat source can be predicted with improving accuracy. A new follow up calculation with a repeated prediction e.g. after day no. 24 would lead to a consistent, outstanding correspondence between the progression of temperature and prediction, respectively.

In general, the example shows that the temperature analysis and prediction program is able to be adapted to a variety of uncertain environmental conditions. It is possible to predict future temperature progression of cable systems in the time frame of several days with only minimal deviations.

8. CONCLUSION

Within this project, a robust and powerful monitoring system has been developed. In cooperation with the industry this system will be developed to a marketable product. By measuring the screen temperatures this system is able to calculate the present conductor temperature, and furthermore it is able to predict future conductor temperatures and load reserves. Critical conditions, such as impending undue conductor temperatures, can be detected in time, and alarm messages can be initialised.

An essential request of such a load monitor is the proper identification of the electrical and thermal parameters of the cables and their environment even when these parameters are rather unknown and may vary along the cable route and are time dependent. Therefore the monitoring and rating program must be able to adapt these internal parameters to the meet the incoming measurement data. To achieve the required robustness of the optimisation procedure, a thermal/electrical model of cable installations is used adapting its parameters periodically by means of a powerful evolutionary algorithm.

By the use of the optimised and periodically adapted model the load monitoring is able to give prediction to:

- expected progression of cable temperatures for the case the current remains constant
- expected progression of cable temperatures for the case of constant load cycle
- permissible constant current over a certain period of time (e.g. 1h, 24h, 1week, etc.)
- highest allowable current for the past load cycle over a certain period of time or
- permissible period of time of certain current (constant or for previous load cycle) until the allowable conductor temperature is reached

In addition a special overload-temperature can also be set in this system.

The RTTR can be verified by comparing the computed values with the data received from an FEM program taking the non-linearities of a real cable route into account.
Critical cases are:

- time and temperature dependent partial drying-out of the soil of the cable route or
- ambient external heat sources that have not been explicitly modelled.

The model’s ability to adapt its parameters is robust and allows to simulate even extreme variations in the cable environment and is still remaining stable. The model is quite simple, and the optimisation procedure can be performed on a standard PC.

In all the investigated cases, the monitoring program shows very good adaptation results with only minor deviations regarding the predictions, which are still well below the measurement uncertainties of common sensor systems.

REFERENCES

[1] Brakelmann, H.; Hirsch, H.; Röhrich, A.; Scheiffarth, H.-P.; Stammen, J.: Adaptiver, prognosefähiger Lastmonitor für Energiekabeltrassen
Report on a DFG-Project, 2006

[2] Stammen, J.: Numerische Berechnung elektromagnetischer und thermischer Felder in Hochspannungskabelanlagen
Dissertation University of Duisburg
Shaker Verlag, 2001

[3] Weissmüller, G.; Worch, M.: Wirtschaftlichkeitsverbesserung in Elektrizitätsverteilungsnetzen durch Auslastungsmonitor für Energiekabelsysteme
El.wirtsch. (1996) H. 9, S. 588-593

[4] Harjes, B.; Peier, D.; Senftleben, H.: Energietechnische LWL-Anwendungen
etz (1992) S. 984-990

[5] Brakelmann, H.: Sensor zur Messung des spezifischen Wärmewiderstandes
Europäisches Patent Nr. 0 672 903 A1, 09.03.1995

[6] Brakelmann, H.: Belastbarkeiten der Energiekabel
VDE-Verlag, Offenburg, 1985

[7] Spice, http://bwrc.eecs.berkeley.edu/Classes/IcBook/SPICE

[8] Brakelmann, H.: Energietechnik programmiert
VDE-Verlag, Offenburg, 1990

[9] IEC: Calculation of the continuous current rating of cables (100 % load factor)
Publication 60287, IEC Standard, 1994

[10] IEC: Calculation of the cyclic and emergency current rating of cables
Publication 60853, 1989

[11] Patton, R.N.; Kim, S.K.; Podmore, R.: Monitoring and rating of underground power Cables
IEEE Trans. PAS (1979) pp. 2285-2293

[12] Brakelmann, H.: Belastungsmonitor für Energiekabeltrassen
etz (1997) S. S. 30-34

[13] Millar, R.J.: A Comprehensive Approach to Real Time Power Cable Temperature Prediction and Rating in Thermally Unstable Environments
Dissertation Helsinki University of Technology

[14] Heinhold, L.: Kabel und Leitungen für Starkstrom, Teil 1
Siemens AG, Berlin/München, 4. Auflage, 1987