INCREASING THE CAPACITY OF CABLE SYSTEMS USING CABLE ASSET MANAGEMENT BASED ON THERMAL AND MECHANICAL PROPERTIES

B.J. Grotenhuis\textsuperscript{2}, J.E. Jaspers\textsuperscript{1}, A. Kerstens\textsuperscript{3}, A.H. van der Wey\textsuperscript{1} and F.H. de Wild\textsuperscript{1}

\textsuperscript{1}: KEMA, \textsuperscript{2}: REMU, \textsuperscript{3}: TKF, The Netherlands

ABSTRACT

An important part of the Dutch energy transport system is directly buried. The medium voltage cable network (below 50 kV) is almost completely buried (>90%) in the Dutch soil, and there is a substantial number of buried high voltage cable systems. All of these cable systems have a characteristic ‘maximum ampacity’ (ampacity = current carrying capacity) based upon the international standard IEC 60287 for stationary cable load. Nowadays, the liberalisation of the Dutch energy market is resulting in higher demands on the electrical infrastructure and therefore, the usage of methods to fully exploit the possibilities of the electrical infrastructure has become very important. KEMA, an independent company for development, certification, testing and consultancy for owners of electrical infrastructure, like utility REMU, uses two methods to increase the effective usage of cable systems. As a first method, cable ampacity management can be used to increase the possibilities of cable systems beyond their current stationary ampacity limits. Secondly, the usage of early warning systems for moisture, developed by TKF together with KEMA, mechanical stress and glass fibre damage can increase the reliability of the infrastructure. Both methods will be discussed in the article.

In the Netherlands, about 250 km of underground cables have been equipped with integrated optical fibres for temperature measurements. From the numerous temperature measurements that were performed on these medium and high voltage cables under normal load, hot spot locations were determined for every cable circuit. These hot spot locations limit the real ampacity of the cable system. The temperature development in time of the hot spot locations has also been measured. When a thermal model could also calculate this thermal behaviour, the real time ampacity (rating) of the cable system could be determined based upon the ampacity history of the cable system under consideration. Because neither the IEC 60287 nor the IEC 60853 can accomplish this task, a new model for buried cable systems has been developed, which meets the following specifications:

1. The thermal model can calculate several interesting cable temperatures, one of which is the glass fibre temperature, which can be used to validate the model using distributed temperature measurements.
2. The thermal model is a general model, and is applicable in many different situations.
3. The thermal model is able to perform on-line calculations, IEC calculations for engineering purposes and calculations for situations without integrated glass fibres (revaluation of existing cable circuits).

The developed model is validated with performed temperature measurements. In order to use the model for ampacity management, the model has been integrated in a custom built graphical user interface. This cable ampacity management system is installed at a cable circuit of utility REMU, and performs on-line ampacity calculations.

Not only thermal measurements and modelling can be used to increase the transport capacity of cable systems. Another method to achieve a better exploitation of electrical infrastructure is the usage of early warning systems in order to prevent cable failure due to mechanical damage. When e.g. an excavator grabs an energy cable, the cable can be electrically damaged. In this case the protection relays detect a short circuit and disconnect the cable. However, the actual damage to the cable an excavator grabs is usually limited to a scratch in the cable’s outer jacket. Through this damaged jacket, water can penetrate into the cable, which will lead (in time) to a failure. In order to detect these indirect electrical failures, TKF has developed a moisture detection system in collaboration with KEMA.

In order to detect extreme subsidence of cables in the softer and weaker grounds, also an early warning system for mechanical stress in the power cable has been developed and furthermore, a detection system for severe cable damage and fibre breakage has been integrated in the prescribed graphical user interface at utility REMU.

The performance of the thermal model is very promising because only a few DTS measurements are needed to validate the rather low cost model. One of the promising capabilities of the complete cable management system is to perform the calculations also for existing cable circuits without incorporated glass fibres. Cable management on mechanical properties allows us to even further utilise the cable system’s capabilities for current transport, minimising the number of unexpected failures and preventing insurance claims.
ABSTRACT

In order to increase the current carrying capacity (often called ‘ampacity’ or ‘cable rating’) and the reliability of underground cable systems, a new form of cable asset management is introduced. The discussed cable asset management tool is based upon the thermal and mechanical status of the energy transport system.

INTRODUCTION

An important part of the Dutch energy transport system is directly buried. The medium voltage cable network (below 50 kV) is almost completely buried in the Dutch soil (>90%), and there is a substantial number of buried high voltage cable systems. All of these cable systems have a characteristic ‘maximum ampacity’ based upon the international standard IEC 60287 for stationary cable load. Nowadays, the liberalisation of the Dutch energy market is resulting in higher demands on the electrical infrastructure and therefore, the usage of methods to fully exploit the possibilities of the electrical infrastructure has become very important. KEMA, an independent company for development, certification, testing and consultancy for owners of electrical infrastructure, like utility REMU, uses two methods to increase the effective usage of cable systems (see also de Wild and Schmetz (1)). As a first method, cable ampacity management can be used to increase the possibilities of cable systems beyond their current stationary ampacity limits. Secondly, the usage of early warning systems for moisture, developed by TKF together with KEMA, mechanical stress and glass fibre damage can increase the reliability of the infrastructure. Both methods will be discussed in this article.

CABLE AMPACITY MANAGEMENT

Manufacturing intelligent cable systems

In the Netherlands, about 250 km of underground cables have been equipped with integrated optical fibres for temperature measurements. Although the integration of optical fibres within energy cables requires some additional specifications, fabrication techniques and experience, glass fibres can be integrated within the energy cable at relatively low cost. In single phase cables, the glass fibres are integrated within the copper wire earth screen of the cable (see figure 1a). Three core cables can be manufactured by incorporating the glass fibres within the central filling element of the three core cable (figure 1b). Cables with an extruded lead sheath instead of a copper wire earth screen can be equipped with glass fibres just under the lead sheath. By incorporating the glass fibres within the cable itself, several interesting possibilities are available. For example, the thermal and mechanical status of the cable system can be determined at any moment in the cable lifetime, without taking the cable system out of service. Using these possibilities efficiently, cable asset management and interesting, funded statements about ampacity possibilities and cable lifetime estimations are possible with this new generation of power cables.

Experience with temperature measurements

By using a commercially available Raman OTDR for distributed temperature sensing (DTS system, spatial resolution: 4m, temperature resolution: 2°C, maximum range: ~25 km), important data about the actual thermal status of a cable circuit can be obtained. From the numerous temperature measurements that were performed in medium and high voltage cables under normal load over the past four years, hot spot locations have always been determined. Sometimes the hot spot can be resolved by adapting the local hot spot situation,
but often the found hot spots are unchangeable and limit the real ampacity of a cable system (not necessarily below the stationary ampacity based upon IEC 60287).

In figure 2 the thermal status of a cable circuit (REMU utility, from substation Oudenrijn to substation SK5) is displayed as a function of the distance from substation Oudenrijn. The temperature differences between the two graphs show that the thermal behaviour of the cable system is very dependent on the distance (or location). This could be expected because the cable system is directly buried in the soil, and no backfill has been used. In figure 2, several hot spots are visible which limit the cable’s ampacity at higher loads.

![Figure 2](image)

Figure 2: Two temperature versus distance graphs showing the temperature at REMU’s cable circuit from Oudenrijn to SK5. The upper curve (red) shows the temperature while the cable circuit carried 430 A while the lower curve (blue) shows the cable temperature while the cable circuit carried 100 A. The lowest green line shows locations where the cables are surrounded by ducts.

It is also possible to monitor the glass fibre’s temperature development in time. Figure 3 shows a graph of the temperature development in the course of time of a certain location. When the thermal behaviour depicted in this graph could also be calculated by a thermal model based upon the current flowing through the cable circuit, the ampacity of the cable system could be determined based upon the ampacity history of the cable system under consideration. With such a thermal model, cable management is possible.

![Figure 3](image)

Figure 3: Temperature development in a location that can limit the cable’s ampacity at higher loads.

**Specifications of the thermal model**

Unfortunately, such a thermal model can not be deduced from the existing ampacity calculation standards IEC 60287 or IEC 60853. These standards focus on the calculation of the maximum stationary load and the response of a cable system on a single step change in the current flowing through a cable system. Therefore, it was decided to develop a new model for buried cable systems that should meet the following specifications.

Firstly, the thermal model has to be able to calculate several interesting temperatures and ampacity ratings within cable system based upon the type of cable, the cable system configuration, soil parameters and the current flowing through the cable system. One of the temperatures the model should calculate is the glass fibre temperature, which should be in accordance with the temperature measured by the DTS system. This connection between model and measurement can be used to validate the model, thereby ensuring that the ampacity statements that will be made based upon the model are as much as possible in accordance with real practice.

Secondly, the thermal model has to be a general model. This means that the model should be able to perform calculations in many different cable circuits and cable configurations.

Furthermore, the model should be able to perform on-line calculations, where the model is used to calculate the real time possibilities for current transport based upon (only) a real time measured current flowing through the cable system. The model should however also be in accordance with the two IEC standards (60287 and 60853) in order to use the same model for improved engineering purposes. In this way, the model can be used not only for IEC standard calculations but also for engineering calculations based upon expected day-night rhythm variations and expected emergency situations. Also, the same model should be able to be used for ampacity calculations in existing cable circuits, without installed glass fibres. This capability can be used to revalue existing cable circuits based on the realised dynamic circuit rating rather than on the (engineered) stationary ratings.

**The thermal model**

A thermal model has been developed which meets many of the stated specifications. The model is developed based upon a thermal R-C network together with a thermodynamic soil heat transfer function. The thermal R-C network lay-out is constructed in such a way that many different cable configurations and cable types can be described by the same R-C network lay-out. The soil heat transfer function is set up in such a way that the
soil input parameters consist of a (real time) soil temperature, the thermal resistivity of the soil and the thermal diffusivity of the soil. These parameters should be determined at the hot spot location by means of a soil survey. To describe the soil with this set of soil parameters is a substantial simplification of reality but it is determined that the correspondence with reality is rather good. Also, it is no sinecure to have much more soil data available for the thermal model when the model is used on many different cable routes.

When the model is used to calculate the temperature at the location of which the dynamics were already displayed in figure 3, the calculated glass fibre temperature is found to be in accordance with the temperature measurement by the DTS system (see figure 4). In this case, one set of soil parameters is used, and the current flowing through the cable circuit was available in half-hour mean currents. Because of the missing history of the circuit load, the model does not correspond with the temperature measurements in the first few days of graph 4. After a few days, the model is found to correspond with the measured temperatures. The modelled temperature is somewhat smoother than the measured temperature because of the effect of the half hour mean current supplied to the model and the accuracy of the DTS system measurements.

Figure 4: The measured (black, upper curve) and the modelled (red, lower curve) describing the temperature development in a location that can limit the cable’s ampacity at higher loads.

It is important to note that the model and the measurement correspond with each other, thereby validating the developed thermal model. In the year 2000, over 10 of these validations were carried out with measurement periods in between two weeks and 1 month. These validations were carried out in different cable routes, with different cable types, cable system configurations and different surrounding soils.

Figure 5 shows several interesting cable temperatures of the REMU Oudendrijn-SK5 circuit, using again only one set of soil related parameters, and validating the thermal model because the calculations correspond closely with the measured glass fibre temperature.

![Figure 5: Several cable temperatures (orange, red, green) and the measured earth screen temperature (black) at the REMU Oudendrijn – SK5 circuit. The model starts at an incorrect (low) temperature because at that moment, the model does not know the ampacity history.](image)

**Cable asset management**

The developed thermal model has been validated for REMU’s Oudendrijn-SK5 cable circuit. The validation with a DTS temperature measurement will be repeated regularly (every 6 months to start with) in order to determine if the soil parameters still describe the modelled situation correctly. Especially in new cable circuits, the soil parameters will change when the soil settles around the newly buried cable system.

![Figure 6: The main screen of the graphical user interface.](image)

To use the thermal model for cable asset management based upon thermal criteria, a customer-dependent graphical user interface (GUI) has been developed by KEMA according to REMU’s needs. The GUI which runs on a stand-alone PC in substation Oudendrijn of the REMU utility is depicted in figures 6 and 7. At the top of figure 6 an impression is given of the two cable routes forming the connection between substations Oudendrijn and SK5. Three hot spot locations are determined, labelled M1, M2 and M3. The hot spot locations are ‘clickable’. In the left bottom corner of the GUI, the current flowing through the cable circuit (online) and the temperature of the conductor are depicted.
by a moving bar. 100% current means the full ampacity (rating) calculated based upon IEC 60287 (stationary ampacity limit). Further, more in the middle of the screen several temperature readings are depicted which are measured on-line by thermocouples. These thermocouples are installed to include variations in the undisturbed soil temperature in the model. The graph at the bottom-right side of the GUI shows the temperatures (conductor temperature = red, cable outside temperature = green) calculated by the developed, validated model and the measured current (blue) at the selected hot spot location. The centre of the graph represents the current situation. At the left of the current situation, the temperatures and the current of the last 24 hours are depicted, and at the right, the temperatures in the following 24 hours are predicted based upon an unchanged current flowing through the cable system. Of course, the history is saved and the prediction time is user definable. In the near future, it will also be possible to show the predicted temperature of the cable circuit based upon a predicted day-night rhythm and based upon an emergency switching operation.

**Figure 7:** On the GUI, this curve shows the cable circuit’s capabilities in case of an emergency.

There is also a button called ‘emergency-rating’ visible on the GUI. When this button is used, an emergency rating graph is displayed, see figure 7. This graph shows how much current can be transported through the cable circuit for a certain amount of time. The curve is calculated based upon the full load history of the cable system, and is updated with every change in the transported current. Based upon the information in this graph, it is possible to decide in favour of switching operations leading to >100% stationary current for a restricted period of time in case of emergencies instead of switching off, thereby preventing power outages.

In it’s present form the GUI is capable of giving answers to the following type of questions:

- Is it possible to transport an emergency current of x amps during for e.g., 12 hours without damaging the cable circuit?
- What are the expected temperatures to be reached in the near future at the outer surface of the cable system and are thermal runaways in the surrounding soil probable?

Because answering these types of questions is now possible on a validated basis and by using the real situation at the limiting hot spot location(s), the cable circuit under consideration can be managed very effectively and very efficiently without damaging the cable system by overheating. The costs of such a cable asset management system are low because only a model, a PC and a periodic temperature measurement for model validation are needed.

The GUI is implemented on a stand alone PC in a substation where the current and thermocouple readings are available on-line. Using the internet, the GUI can be accessed at any location by using a modem. Future developments will be directed to integration with SCADA systems in which the current and thermocouple information is transported to the location where the thermal model is running (e.g. control room). In this way, cable management can be extended to cable network management.

**EARLY WARNING SYSTEMS**

Not only thermal measurements and modelling can be used to increase the transport capacity of cable systems. Another method to achieve a better exploitation of electrical infrastructure is the usage of early warning systems in order to prevent cable failure due to mechanical damage.

**Early warning system for moisture**

In the Netherlands, the main fault cause in buried medium voltage circuits is mechanical damage due to excavation. When an excavator grabs an energy cable, the cable can be electrically damaged. In this case the protection relays detect a short circuit and disconnect the cable. However, the actual damage to the cable an excavator grabs is usually limited to a small scratch in the cable’s outer jacket. Through this damaged jacket, water can penetrate into the cable which will lead (in time) to a failure. To prevent these failures, an integrated moisture sensor has been developed by TKF and KEMA with a response time in the order of minutes. This integrated moisture sensor will give an alarm before the cable fails, so that the cable can be repaired prior to the expected failure.
Early warning system for mechanical stress

Another very frequent cause of underground cable failures in the Netherlands is the extreme subsidence of cables in the softer and weaker grounds. Ground subsidence will lead to an increased mechanical strain in the energy cable, which will result in a significantly shortened cable life-time. To have an early warning for this kind of failures, an incorporated glass fibre packaged in a semi tight tube can be used in combination with a distributed Brillouin scattering measurement (BOTDR, commercially available). Extreme subsidence or bending (interesting for installation procedure evaluation) will result in a strain in the glass fibre sensor, which leads to an altered glass fibre Brillouin scattering frequency. The frequency shifts can be determined by performing BOTDR measurements and to focus on relative change in Brillouin frequency. In this way, the relative strain in a cable system can be determined and according actions can be taken.

Early warning system for severe damage and breakage

A very elementary early warning technique is also incorporated in the GUI which was shown in the paragraph concerning cable asset management. In the top-right corner of figure 6, two traffic lights can be seen (one traffic light for each of the two cable routes). These traffic lights monitor changes in the attenuation of the incorporated glass fibres. When e.g. an excavator grabs the cable (which is in a building area) and the glass fibre breaks or is severely stretched, the glass fibre’s attenuation is suddenly increased. This sudden increasing attenuation can be detected by a simple detector-receiver configuration, which was implemented in the thermal cable management system. When an increase in attenuation is detected, the traffic light will switch to yellow, and an incorporated OTDR measurement is performed (within about 1 minute) to locate the precise location and attenuation change in the glass fibre under consideration. When a significant change in the glass fibre attenuation is measured, the traffic light will switch to red, thereby indicating the exact distance from the substation where the attenuation increase was measured. The same detection procedure can also be used for the early warning for moisture ingress.

In this way, a cheap and trustworthy system for the early warning of mechanically induced electrical failures in the cable system is incorporated in the cable management system. The early warning of such failures can prevent unexpected outages and can thus prevent expensive insurance claims.

When the early warning system is expanded to incorporate a moisture sensor, a mechanical sensor and a sensor for severe damage, the system will have a number of different benefits above other cable systems. An important advantage of such a complete early warning system will be that it distinguishes between the different parameters and that a location of the fault is given in a relative short time (minutes rather than hours). The fast determination of the fault location results in a faster repair of the cable and therefore less non-delivered power and lower insurance claims.

CONCLUDING REMARKS

A thermal model which is validated by temperature measurements (either using glass fibre or using thermocouples in the older infrastructure) has been used to perform asset management on a cable system of the REMU utility. The model is applicable for many different cable types and cable configurations and can be used to answer several questions about cable ampacity. Also an elementary glass fibre breakage sensor is incorporated in the REMU cable management system to give an early warning for mechanically induced electric failures. It has been shown that early warning systems can prevent cables from unexpected outages thereby preventing insurance claims.

For the case of thermal cable ampacity management as described, REMU has performed a life cycle cost analysis in which REMU compared the cable system with a cable asset management system (thermal) to the same cable system without a cable asset management system. REMU found out that in the present situation, which is not uncommon at REMU and at other Dutch utilities, the differences between costs and benefits is largely in favour of the cable asset management system.

The performance of the thermal model is very promising because only a few DTS measurements are needed to validate the rather low cost model. One of the promising capabilities of the complete cable management system is to perform the calculations also for existing cable circuits without incorporated glass fibres.

Cable management on mechanical properties allows us to even further utilise the cable system’s capabilities for current transport, minimising the number of unexpected failures and preventing insurance claims.

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