FIBRE-OPTICAL TECHNOLOGY IN MEDIUM-VOLTAGE XLPE CABLES IN THE NETHERLANDS

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SUMMARY

Within one year, a pilot project has been realised in Utrecht, involving a medium-voltage XLPE transport cable with two integrated optical fibres. The joints and terminations have been specially adapted to fit this 'smart cable'. The smart cable and its accessories have been tested thoroughly. The optical fibres have been used for periodic temperature measurements and for cable protection. The conducted temperature measurements have been used for cable current transport capacity management. Both cable management and protection can be realised for an acceptable price.

INTRODUCTION

As was announced in Birmingham [1], a pilot project has been realised within one year in the Leidse Rijn district of Utrecht, involving a medium voltage XLPE transport cable with integrated optical fibres: the TwenOptopower cable. One optical fibre is used for temperature measurements and current transport capacity (ampacity) management of this 'smart cable' system. A second fibre is used for cable protection.

This pilot project is part of a large research programme focusing on the use of 'intelligent high and medium voltage cables and lines', funded by the Dutch distribution companies and undertaken by KEMA on behalf of EnergieNed. The aim of this programme is to pilot 'smart' cable systems in the Dutch electric energy transport network. The project involved close co-operation between KEMA, REMU (the user of the cable system) and TKF (the manufacturer of the 'Optopower' cable).

PROJECT DESCRIPTION AND AIM

The aim of this pilot project was to determine the technical and economical value and feasibility of a smart cable system.

Especially medium voltage transport cables are subject to considerable loads and are installed in extremely diverse conditions. The user therefore wishes to have an effective cable management system utilising the capabilities of integrated optical fibres. By intelligently using the optical fibres for cable operation, monitoring and management, considerable economic advantages can be achieved in the future.

The lifetime of a XLPE cable will be drastically decreased when the isolation layer of the cable exceeds a certain temperature. Therefore, it is important to be able to detect (and predict) the cable temperature for a cable transporting a varying, dynamic, current. Together with an optimal differential protection, these distributed temperature measurements were the primary aims of this pilot project.

In the near future experiments will be performed in order to detect a relative humidity (RH) level in the cable exceeding 70 % and also mechanical strain and -pressure within a cable, using the integrated optical fibres. Furthermore, the ageing and fracture of the integrated optical fibres themselves will be examined.

CONSTRUCTION, TESTING AND INSTALLATION OF THE CABLE, OPTICAL FIBRES AND ACCESSORIES

The XLPE medium voltage transport cable (type: YMeKrvaslwd 6/10 kV 1x400 Alrm + as 70) was constructed according to the Dutch NEN 3620 standards.

Figure 1: Medium-voltage XLPE cable with two single mode optical fibres in the copper wire screen.

The cable is equipped with two single-mode optical fibres enclosed in plastic loose tubes within the copper wire screen. The cable construction is shown in figure 1.

The following specifications, which are commonly used for standard telecommunication fibres, are required for the single mode optical fibres (attenuations at 1550 nm):

- the bare fibres all have to originate from the same batch of fibre

- the bare fibre attenuation has to be less than 0.23 dB/km
- the fibre attenuation in the manufactured, reeled cable, has to be less than 0.25 dB/km
- the attenuation of a fibre fusion splice has to be less than 0.05 dB
- the overall fibre attenuation after cable installation has to be less than 0.30 dB/km.

Furthermore, the plastic loose tubes, which enclose the optical fibres, must be able to withstand brief-duration temperatures of up to 350 °C.

The joints and terminations were adapted by the suppliers in order to suit this combined electrical / optical cable (see also figure 2). In each joint, an organiser is included to house the fusion spliced optical fibre. Each termination is fitted with an underside outlet accessory, via which the optical fibres can safely be passed from the cable to a connection box. Inside this box, the optical fibres are connected (by a fusion splice and an organiser) to a normal fibre-optic cable.

The attenuation of the optical fibres was measured both during and directly after cable manufacturing. Furthermore, the construction including all accessories was checked mechanically. This involved the usual cable survey, plus extra cable tension and -torsion tests developed for this project. Cable realisation was undertaken by TKF on a turnkey basis (see for an example figure 2).

The complete cable circuit was tested after laying using an alternating voltage with a frequency of 0.1 Hz, combined with a loss angle test. OTDR (attenuation) and BOTDR (mechanical tension) tests were performed on the optical fibres, in order to check the quality of the optical connections prior to handing them over to REMU. The attenuation in the optical fibres proved to be well within the specified limits stated above.

Figure 2: Three electrical / optical joints, made by TKF. The two white strings in the right joint contain the glass fibres, and lead to the white / grey organiser.

PROTECTION OF THE CABLE

No cross bounding is used in the earthing circuit. However, in each joint the standard 70 mm^2 earth screens are connected to each other between the joints using an insulated 95 mm^2 copper wire (see figure 2).

The neutral in REMU's 10 kV network is insulated. Usually, 10 kV earth faults are identified but no switching action will follow. However, for safety reasons it was decided that single-phase XLPE cables have to be switched off when a single-phase fault occurs. In contradiction to a single-phase fault in a PILC cable, a similar fault in a single-phase XLPE cable can result in dangerously high voltages at the fault location. The chance that a single-phase fault develops in a three-phase fault is quite small for XLPE cables.

In order to be able to quickly and effectively switch a cable 'out of action', and to have a protection which is independent of the used cable fibre, zone differential protection is used in combination with an earth fault directional relay. Two optical fibres are necessary for communication between the two zone differential relays, and use is made of active re-routing. This implies that the protection would continue to function if one of the optical fibre circuits is interrupted.

As a backup protection system, a maximum protection at the supply station is used. In the event of a single-phase fault, the earth fault directional relay in the switching station would close a breaking contact connected to a digital input on the longitudinal differential relay. The circuit breaker in the supply station would then trip once the input was activated. In this way, provision was made for isolating earth faults at both ends. See also the protection scheme in figure 3.

Using fibre-optics, reserve cables can easily be continuously monitored for damage via a terminal joint in combination with a field protection relay. The advantage of this approach is that there is no need for a high monitoring voltage or a high voltage terminal joint, and therefore, there is no safety risk.

In the future, it should be possible to protect cables and cable PE jackets against damage and moisture penetration by using the optical fibres for distributed (localised) early detection of glass fibre fracture, undue mechanical pressure, mechanical strain and the presence of moisture in cables, before the situation reaches the point where the electrical protection would trip.

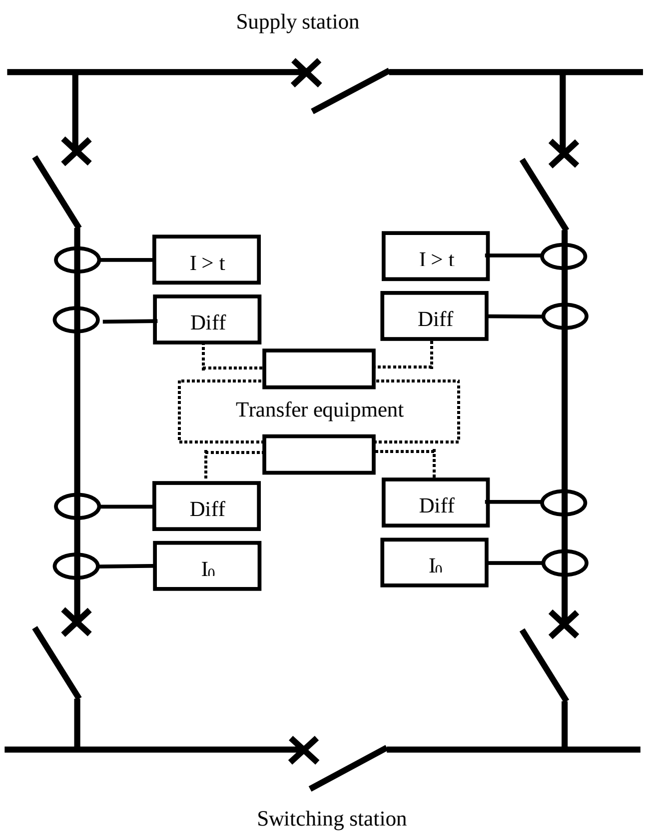

Figure 3: Protection concept based on two zone differential relays with active re-routing, backed up by a maximum protection.

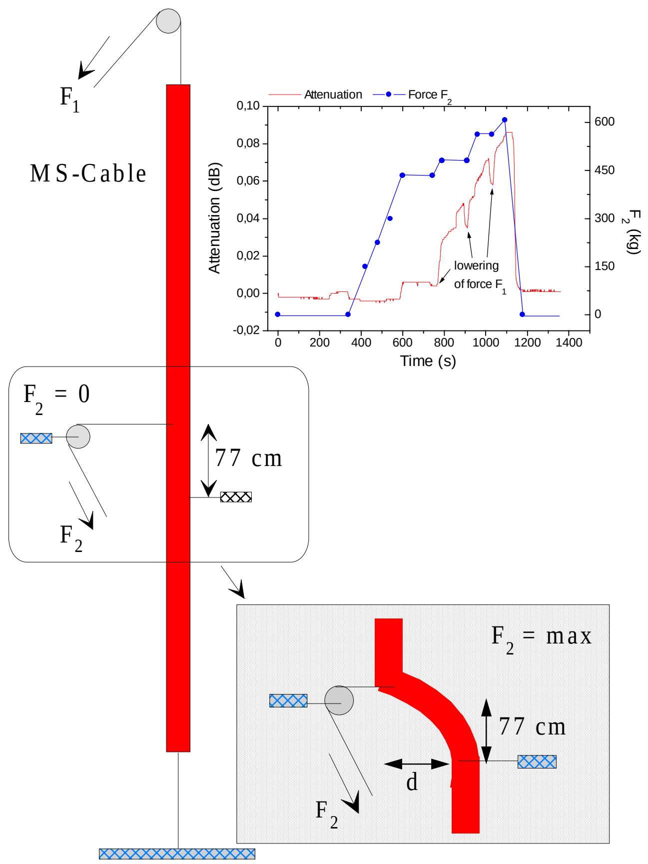

Figure 4: Set-up for the application of lateral force to a medium-voltage cable. In the graph, the attenuation and the applied force are plotted as functions of time.

MEASUREMENTS OF MECHANICAL FORCES USING THE INTEGRATED OPTICAL FIBRE

Each of the medium-voltage XLPE cables installed by REMU in early 1999 was provided with an optical fibre for the detection of mechanical forces. To check the cable construction, a tension test with lateral loading was carried out in addition to the usual cable tests, in order to simulate ground subsidence. A diagram of the test set-up is presented in figure 4, together with the test results. From the data obtained, it is clear that attenuation rises as the lateral force applied (F_2) is increased and falls again if the longitudinal tension within the cable (F_1) is reduced.

The project also examined the possibility of introducing new monitoring and protection techniques based on optical fibres incorporated in the copper wire screen. It was established that distributed (localised) detection of faults at which mechanical damage is occurring is possible. Using this technique, it is possible to detect tension in- or pressure on the cable, PE jacket damage, or cable fracture. Periodic testing of the cable at different loads can provide a good picture of the cable's underground behaviour.

Rapid and accurate distributed detection of mechanical forces and damage is possible. Although nowadays cables are tested periodically, continuous monitoring is a realistic option for the future. By monitoring mechanical forces continuously, it is possible to carry out preventive repairs (before an electrical fault occurs). This ensures the complete reliability of a continuous monitored smart cable connection. Both direct (preventive repairs) and indirect costs (ceasing energy delivery) can be saved using this principle of continuus monitoring.

TESTING FOR MOISTURE PENETRATION WITHIN THE STRUCTURE OF THE CABLE

The next objective of the project is the distributed detection of moisture penetration in a cable by means of periodic testing. Another pilot project is to be organised in the near future, in which a further optical fibre, primarily intended for moisture detection, will be incorporated in the copper wire earth screen.

Moisture detection is believed to be possible using a specially modified fibre. A laboratory scale working model is now in use. In this set-up, a special fibre is wound around an optical fibre (see also figure 5). The special fibre shrinks on contact with moisture, thereby increasing the attenuation in the optical fibre. In figure 5, the sensor as well as an

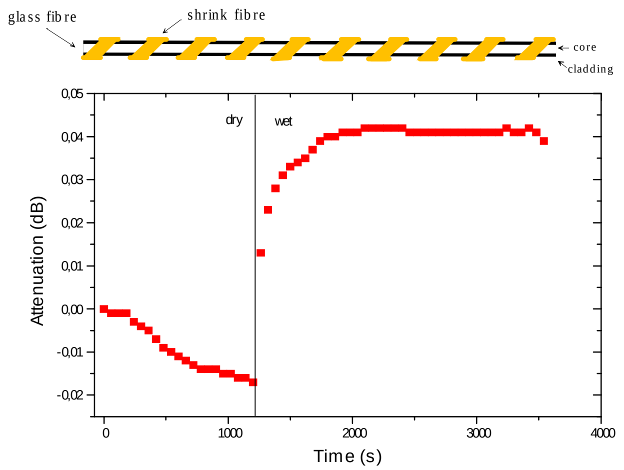

Figure 5: Trial moisture sensor consisting of a shrink fibre wrapped around an optical fibre. The graph shows the attenuation as a function of time. The sensor was wetted after 1200 s.

attenuation graph showing the sensor's response on moisture, are shown.

In the course of 1999 an attempt will be made to construct and test a trial cable which incorporates the moisture sensitive fibre.

With such a cable with an integrated moisture sensor, in wet soil it will be possible to detect small cable fractures or cable (PE) jacket damage before electrical faults occur. The sensor should be able to detect relative humidities in excess of 70%, since water tree formation can occur at higher humidity levels.

This integrated sensor is a very promising tool for condition dependent, preventive, maintenance of cable systems. Another important advantage of the system is that there would be no need for 5 kV direct voltage testing, for which the cable has to be 'out of function'.

Ideally, only one optical fibre capable of detecting both mechanical forces and the presence of moisture should be developed and incorporated in the, already, smart cable.

THE CABLE MANAGEMENT SYSTEM AND ITS RECENT RESULTS

The integrated optical fibres in the XPLE cable can be used to manage a cable's current transport capacity (ampacity). Not only the (statically engineered) current transport capacity be can fully exploited, but also the maximum emergency current transport rating can be calculated, and predictions of the actual cable temperature can be made. The cable management system thus helps to fully utilise the cable's current transport capacity.

The cable management system consists of two separate elements. The first involves optical temperature measurements by usage of the integrated optical fibre. The second involves the use of a dynamic thermal model for temperature, and therefore, ampacity, calculations. These two elements are discussed in turn below.

The integrated optical fibres can be used for distributed temperature measurements. Such measurements have been conducted in the Netherlands at several locations, using the York DTS 800. This device is in fact a simple OTDR, capable of detecting the Raman-backscattered light instead of the Rayleigh-backscattered light. Because the intensity of the Raman-scattered light depends largely on the temperature of the glass fibre, the combination of an OTDR and a Raman wavelength sensor results in a distributed temperature measuring device. The York DTS 800 is capable of detecting temperatures with a resolution of ± 2ºC and a spatial resolution of ± 4 metres.

An example of a distributed temperature measurement is shown in the figures 6 and 7. The two graphs relate to a measurement performed at the Dutch ENW utility. In figure 6, it can be seen that there are two clearly different 'levels' of temperature in the cable circuit. These are found to correspond to a measured difference in soil thermal resistivity; a parameter which plays an important role in determining the maximum current transport rating. When the distance axis in this figure is expanded, specific hot and cold spots in the cable circuit can be localised very accurately.

In figure 7, the temperature of two different locations (one at the higher temperature level of figure 6, one at the lower level) are plotted in time, together with the current flowing through the cable. This current is found to vary according to the common day-night rhythm which is usual for this type of transport cable. However, a similar rhythm is found in the cable temperature. The cable temperature proves to vary not only according to a rhythmic day-night pattern, but also according to longer-term patterns. For example, there is a weekly rhythm: on Mondays, the daytime temperature of the cable is appreciably lower than it is on Fridays, although the current flowing through the cable is about the same or less than that flowing on Mondays.

These effects can clearly be measured by using an intelligent cable in combination with a Raman-OTDR.

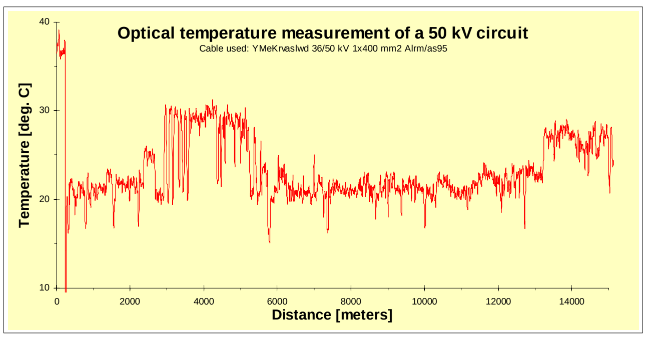

Figure 6: A temperature versus distance graph of a 50 kV XLPE cable (burial depth: 1.2 m, current flowing: 300 A, max static current: 700 A).

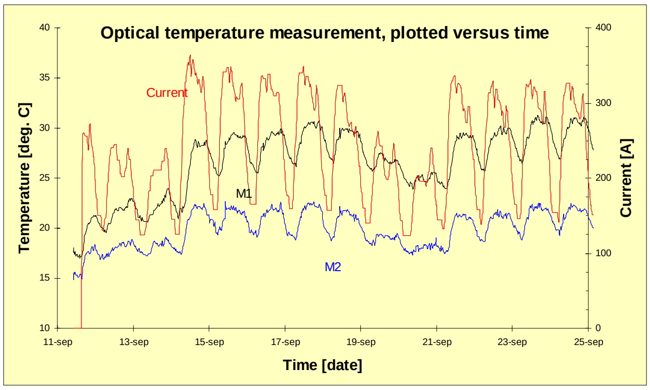

Figure 7: A temperature versus time graph corresponding to the graph in figure 6. Traces M1 and M2 correspond to a certain position (M1 = high, M2 = low) in figure 6.

When these results are combined with a model, conclusions can be drawn regarding the ampacity and the maximum permissible ampacity. To do so, a dynamic thermal model is used. A static model, such as IEC 287, cannot be used to make predictions because it is not possible to input variable dynamic current data. Therefore, KEMA used an adapted version of the IEC 853-2 dynamic thermal model. This model can be used to predict a cable's temperature using variable current data. In this way, using the actually measured cable temperatures and a dynamic IEC model capable of temperature predictions, clever statements about the dynamic current transport capacity can be made.

In the near future, the combination of temperature measurement and dynamic thermal modelling will result in a cable management system capable of verified and practice-related dynamic ampacity control.

COST-BENEFIT ANALYSIS

With its parallel single-phase XLPE medium-voltage transport cables, the pilot project represents a double innovation for REMU:

1. In the past, distribution stations were radially supplied using 3x150 mm^2 PILC cables. In this pilot project, parallel single-phase medium voltage transport cables were used to supply such a distribution station. Because of the greater conductor cross-section of the cables, a greater field utilisation for the station was realised. Beside a substantial cost reduction (around 10 %), the supply reliability, and therefore the electric connection quality, was improved by a factor 1.5.
2. Optical fibre technology is used for integrated optimal zone differential protection and distributed temperature measurements:
   - In the past, a separate optical fibre has been laid alongside the electricity cable in a PE tube. To establish a redundant connection, a second parallel optical fibre circuit was required. In the pilot project, an optical fibre is incorporated in each cable core within the earth screen at relatively low cost. Redundancy can then be achieved much more cheaply by active re-routing via the cores of the parallel smart cable circuit.
   - The pilot project makes distributed temperature measurements possible at an affordable cost.

Because smart cables offer the possibility for temperature monitoring, dynamic ampacity management and thus, optimal cable utilisation, is possible, as is temperature prediction in overload situations. By using this ampacity management system, considerable savings can be achieved by extending cable life. This leads to the (controlled) postponing of the capital expenditure involved in laying additional circuits.

Furthermore, the measured temperature data can be used in the development of software for both stationary and dynamic maximum load calculations. In the future, it will be possible to revise the standards currently in use (IEC 287 & 853-2) on the basis of accumulated verification calculation data.

Another advantage of the usage of smart cables is the possibility to accurately localise hot spots caused by local heat sources or poor heat conduction in the soil by usage of the Raman-OTDR system. Appropriate corrective action can then be taken, so that the service life of the cable is not compromised. The present approach is based on regular testing, for statistical operational purposes. Such a system can extend cable life by a number of years, thereby reducing life cycle costs considerably. In the future, continuous monitoring as a basis for dynamic operation will be an option (dynamic cable management system). On-line management can make it possible to postpone the capital expenditure involved in extending or replacing older cable systems.

The use of differential protection enables cables with faults to be switched off very quickly, which in turn extends the service life of the cable circuit.

Also, the optical fibre technology is an attractive tool for accurately localising faults in cables without using high voltage test techniques. A great advantage of using optical fibres as sensors in cables in the case of fault location, is that periodic testing or on-line cable condition monitoring are possible while the cable core is under load and in use. By contrast, voltage tests, PE jacket tests, loss tangent tests and partial discharge tests all involve taking the cables out of service.

Nowadays, various draft specifications can be provided for this type of medium-voltage XLPE cable. The intention is to standardise specifications, inspection plans and cable construction. At present however, insufficient experience and data is available for the formulation of definitive standards.

THE FUTURE

In the future, we intends to carry out further projects involving the use of optical fibres for centralised tariff switching, the operation of lighting in public places, and the remote monitoring of measurement devices.

In the longer term, optical fibres will be used for direct cable protection based on the distributed (localised) optical measurement of current. Such a system would be a new approach to distance protection for cables.

CONCLUSIONS

The pilot project was successful and was completed in only one year. The cable is robust and reliable, as is evidenced by the following points:

- The overall attenuation within the cable circuit was well within the attenuation requirements applied to telecommunications cables.
- The “Mercedes test” (the accidental running over of the cable by a Mercedes car) did not result in damage to the cable or its integrated optical fibres.
- An initial fault caused by mechanical damage brought about by a mechanical digger entailed only very localised damage to one optical fibre.

The smart cable has been used extensively in the last year. The conclusions reached during cable operation are:

- Optopower medium-voltage transport cables are very promising. The measurement technique was verified by this project and found to be suitable for use in dynamic cable load management control. The dynamic cable load will be measured over a given period and will be modelled. Overloads of 130 % lasting for four hours appear feasible.
- As well as enabling the verification of IEC 287 and the dynamic use of cables, the new system will provide information regarding maximum core and mantle temperatures and regarding soil drying.
- The results of the project indicate that cable management can be introduced at an acceptable price.
- The protection concept works well and is reliable.
- Using the fibres incorporated in the cable, or by means of separate optical current sensors, in the future it will be possible to introduce new, smart, protection concepts and to identify faults at an earlier stage and more quickly.

ACKNOWLEDGEMENTS

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