A PRACTICAL APPROACH TOWARDS OPTIMIZING THE UTILIZATION OF MV CABLES IN ROUTINE NETWORK PLANNING

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ABSTRACT

The paper describes the approach of Essent Netwerk B.V. towards optimizing the utilization of MV networks in order to reduce expenditures while not compromising the performance as measured by the company's other business values. First, the topology and operation of the MV networks in the Netherlands are described. Then an introduction towards thermal modeling of MV cables is given and some examples are shown. Finally, the translation of the results of the investigations into a practically applicable "Cable Loading Guideline" is discussed.

INTRODUCTION

Transmission and distribution networks used to be considered as a natural monopoly. In order to prevent abuse of their monopoly position by network operators, regulating bodies are created. These protect customers that depend on the networks for the supply of a vital resource. Although the regulatory approaches adopted by these bodies vary, their aim is to increase in some way or the other the effectiveness and efficiency of the network operators; in other words to achieve both lower tariffs as well as an increase in supply reliability for customers connected to the network.

It can be easily imagined that the increasing political and public expectations, together with the income decreases being faced by network operators, lead to a pressure on cost. Consequently, it becomes evermore important to justify any expenditure by showing that it either prevents a larger expenditure in the future, or that it is an efficient way of serving the business values of the network owner. A purely technical argumentation (such as a certain supposed lifespan or nameplate capacity) is thus in principle not sufficient anymore to justify expenditures, unless such technical argumentations have been thoroughly linked to the company's business values (or in case this is not yet possible, which may make it appropriate to rely on a technical argumentation at least for the time being).

Amongst the candidates for reducing the investments in the network is the reinforcement of medium voltage (MV) networks, which involves significant investment volumes. It is clear that at some point in time, investments in network reinforcement are inevitable. However, for two reasons it is worthwhile to postpone such investments as long as possible by optimally utilizing the capacity of the existing MV infrastructure. First, this leads to NPV (Net Present Value) savings, as an investment somewhere in the future is "cheaper" than an investment today. Second, additional knowledge arises over time. This can lead to a solution that differs from the original one due to developments such as new residential or industrial consumers or the connection of distributed generators and may even lead to a complete abandoning of the investment. The increasing utilization of the MV networks should, however, of course not have significant negative consequences for the company's business values that could outweigh the obtained gains pushing the overall cost-benefit balance to the wrong side. In this paper, the approach of Essent Netwerk B.V. towards optimizing the utilization of MV networks in order to reduce expenditures while not compromising the performance as measured by the company's other business values is described. First, the topology and operation of the MV networks in the Netherlands are described. Then an introduction towards thermal modeling of MV cables is given and some examples are shown. Finally, the translation of the results of the investigations into a practically applicable "Cable Loading Guideline" is discussed.

MV NETWORKS IN THE NETHERLANDS

MV Cables

In the Netherlands, virtually the complete LV (230/400 V) and MV (> 1 kV to < 50 kV) infrastructure consists of cables and LV and MV overhead lines hardly exist. The two main types of MV cable occurring in the Netherlands are PILC (Paper Insulated Lead Covered) and XLPE (Cross Linked Poly Ethylene) cables. The first type, PILC cable, has been used for several decades, so that large parts of the present networks consist of this type of cable. However, during the last 20 to 30 years it has been gradually replaced for new installations by XPLE cable and no PILC cables are installed anymore today.

Either copper or aluminium can be used for the conductors of both PILC and XLPE cable. Cables with a relatively small conductor cross-section (i.e. up to about 200 mm^2-250 mm^2) exist both as single core and as three core cables. Larger cross-sections are manufactured as single core, because as three core they would become too heavy and difficult to handle and bend.

Topology and Operation of MV Networks

The typical topology of MV networks in The Netherlands is depicted in figure 1. A MV bundle or network is fed by a (regional) transmission network through a HV/MV transformer. Typical primary voltages of HV/MV transformers in The Netherlands are 220 kV, 150 kV, 110 kV and 50 kV; typical secondary voltages are 25 kV, 20 kV and 10 kV. When the primary voltage is relatively high (e.g. 110 kV and higher) and/or load density is low, a MV-transmission step is introduced between the transformer and the MV-distribution feeders. If the primary voltage is low and/or load density is high, MV-distribution feeders are directly connected to the MV-installation fed by the HV/MV-transformer. MV-transmission can be carried out either at the same voltage as MV-distribution, in which case no MV/MV-transformer is necessary in the MV/MV station, or at a higher voltage (e.g. MV-transmission at 20 or 10 kV and MV-distribution at 10 kV or 3 kV respectively). MV-distribution feeders are generally constructed as two half rings which are opened somewhere. In figure 1, MV networks with and without MV-transmission are depicted schematically in their most straightforward form. More complex variations frequently occur, in which for instance a MV/MV station is fed not only directly by cables from the HV/MV station, but also by cables from another MV/MV station. Besides, many MV-installations at HV/MV substations feed both MV-transmission networks and MV-distribution feeders and not all distribution feeders feature the pure ring shape.

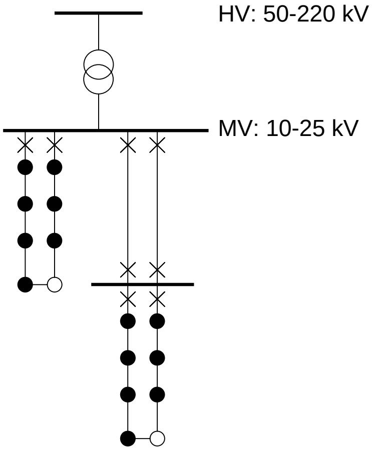

Figure 1. Typical topology of MV networks in the Netherlands; without and with MV-transmission

MV-transmission bundles or networks normally meet the (n-1) criterion, which means that when all cable circuits are in operation, every cable circuit in the bundle or network can be lost without causing an overload of any other cable and without any interruption of supply. Meeting the (n-1) criterion also facilitates maintenance, as one cable can be easily taken out of service for carrying out maintenance.

MV-distribution feeders are not inherently (n-1) safe. When a fault occurs in the feeder, it is disconnected by the switch at the sending end, resulting in the loss of the load supplied by the feeder (either directly or through the LV networks connected to the MV distribution feeder). However, in general, distribution networks are planned and constructed in such a way that after isolation of the faulted feeder cable section, all load can again be supplied by reconfiguring the network.

MODELLING THERMAL BEHAVIOUR OF MV CABLES

Importance of Cable Temperature

In case of MV cables, which form the subject of this paper, one of the factors determining the aging rate is the operating temperature of the cable. The higher the operating temperature, the more rapidly chemical reactions, such as aging, progress. This is caused by the fact that more energy is available for the chemical reaction. This relation is mathematically formulated by the Arrhenius equation:

$$k = A \cdot e^{(-E_a/RT)}$$

where k is the rate coefficient, A is a constant, E_a is the activation energy, R is the universal gas constant, and T is the temperature (in degrees Kelvin).

Up to this moment, cable failures due to thermal degradation hardly occur. Reasons for this are:

- Historically, cables were often quite lightly (thermally) loaded. This was caused by, amongst others, the level of redundancy in MV networks, doubts about the thermal endurability of joints and terminations and not taking into account the thermal dynamics of cables (see also in the next section).
- Due to the high load growth in the past, high cable loadings occurred, if anyway, only for short periods of time, because load quickly was so high that network reinforcement was necessary.
- Because often cables with small cross sections used to be applied, many of these have even been completely put out of service before they could seriously degrade, because as soon as load even slightly grew, such cables had too little capacity.

Besides, cultural and institutional factors played a role. Cultural factors are for instance the generally conservative approach of utilities and the (one-sided?) emphasis on reliability of supply; an example of an institutional factor is the historical cost plus tariff regulation schemes under which many utilities used to operate.

However, in developed countries, the situation is completely different nowadays. Load growth has in general been reduced to modest rates of a few percent, so that cables can be highly loaded (at least during (n-1) situations, i.e. for relatively short periods of time) for years before load has grown so much that network reinforcement is considered necessary. This also results in a generally longer service life of cables. Observations like these would plea for a(n even more) conservative approach towards determining cable loadings. However, the yardstick regulation schemes adopted by most regulators push into the opposite direction. Overall, these developments result in the necessity to rigorously balance cost and risk (i.e. negative impact on the company's business values) in the determination of the rating of MV cables.

Of course, these developments also require an explicit and careful consideration of other cable aging phenomena, such as moisture ingress, water treeing in older XLPE-cables or the effect of chemicals in polluted soil. However, opposite to aging due to higher temperatures, these aging phenomena and the underlying physical mechanisms are very difficult to model mathematically, depend much more on local circumstances and differ much more between individual cable designs and manufacturers. Therefore, if needed, inspections and measurements are a more suitable approach to determine the state of a cable and the extent of aging due to these phenomena. Therefore, the scope of this paper is limited to the topic of thermal degradation. However, other aging phenomena are discussed more elaborately in [1]..

Thermal Modelling of MV Cables

MV cables carry current and withstand an electrical field and thus transport electrical energy. Both these functions are, however, not performed ideally, so that some of the energy is dissipated and heat is developed in the cable.

Several modelling approaches exist to calculate the temperature of a cable conductor or the outer cable sheath that results from the cable's dissipation. In general, there is an important distinction between stationary and dynamic approaches for thermal calculations. In stationary approaches, such as described in the international standard IEC 60287 [2] and the Dutch Practice Guide Lines (Nederlandse Praktijk Richtlijn, NPR) 3107 and 3626 [3, 4] it is assumed that the cable carries a continuous current, which results in a continuous temperature distribution. The IEC 60287 contains a method to calculate core and sheath temperature under such circumstances. The NPR contains tables with frequently occurring cable types and their continuous ratings when assuming a certain temperature limit under given, defined circumstances.

However, MV cables in electricity networks do in general not carry a constant current. The current fluctuates during the day and the week and can also change significantly due to an outage of a MV transmission cable or a reconfiguration of a MV distribution network. Due to the construction of MV cables, they have quite long thermal time constants. This means that a change in the current (and hence in the losses) causes a far slower change in cable temperature, so that it takes quite long until the new stationary temperature distribution will be reached.

The dynamic thermal behavior of MV cables can be taken into account in dynamic calculations. For specific cases and assumptions, these are covered in the international standard IEC 60853 [5]. In figure 2, some calculation results using the IEC 60853 are presented.

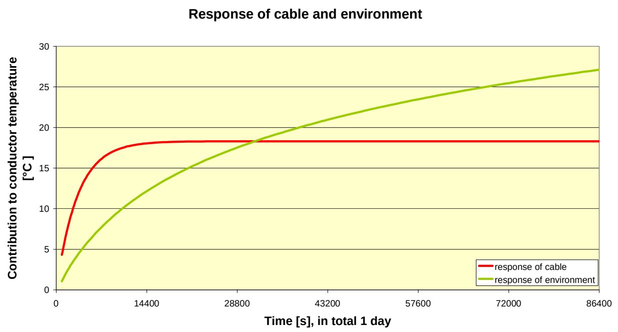

Figure 2. Example of thermal calculations using IEC 60853

The IEC 60853 has a number of limitations. The most important is that only step changes in current and emergency and cyclic current ratings for a constant cycle can be calculated. For a more accurate analysis and an analysis of more sophisticated cable types and current patterns, a complete dynamic model would be necessary.

KEMA developed such a fully dynamic thermal model based on the experience gathered with many temperature measurements with integrated (or nearby) optical fibers [6]. These Distributed Temperature Sensing (DTS) measurements provided the information needed to set-up a physical model of a power cable in its environment which corresponded with both the applicable IEC standards (IEC 60287 and IEC 60853) and the much more dynamic loadings and temperatures measured in practice. KEMA's fully dynamic thermal model can be used to predict the cable's current carrying capacity in the future. Because the model is a true physical model, the presence of a glass fibre is not required, the model is appliccable to both cables with glass fibers for temperature measurements and cables without glass fibers.

By applying the model, the cable loading can often be structurally increased without overloading (thus: without exceeding certain temperature limits) a cable circuit because usage is made from the thermal inertness of underground power cables. The techniques therefore have an economical impact because of the postponement of investments in new cable circuits. At Essent Netwerk B.V., it turned out to be possible to increased loading possibilities significantly by using dynamic rather that stationary thermal modeling of the MV power cables. However, these modeling techniques can only be applied successfully when the thermal bottlenecks can be located systematically and when sophisticated knowledge of the thermal behavior of power cables in thermal bottlenecks is brought in. KEMA, being one of the first to step into these new techniques, can already refer to over 7 years of experience with on-line dynamic thermal modeling and even more with scenario modeling and DTS temperature measurements.

A PRACTICAL APPROACH TOWARDS A MV CABLE LOADING GUIDELINE

Background of Guideline

As discussed in the last section, due to the relatively long thermal time constants of MV cables, the cable current can temporarily be allowed to exceed the continuous rating without the cable temperature exceeding its maximum allowable value. Combined with the fact that MV networks in The Netherlands are either (n-1) safe (MV transmission) or reconfigurable (MV distribution), so that MV cables are generally lightly loaded and therefore have a relatively low temperature during normal operation, this makes it possible to allow a significantly higher current during irregular grid operation without exceeding the maximum cable temperature, which is the primary quantity of interest. This observation makes it, at least theoretically, possible to improve the utilization of MV cables without exceeding the maximum permissible cable temperature and thus without accelerating aging and/or compromising reliability of supply.

In order to indeed utilize the thermal behavior of MV cables beneficially in routine network planning, a method that the people carrying out this task are able to apply in every day practice must be available. To this end, a number of boundary conditions must be fulfilled, such as:

- The method must match the competencies of the employees responsible for MV network planning. This implies that no extensive and advanced calculations and simulations should be required.
- The data required to apply the approach must be readily available or at least be relatively easy obtainable.
- The efforts and cost of application of the method must be in balance with the achieved savings.

Development of Guideline

Essent Netwerk B.V. has consistently organised itself in accordance with the Asset Management organization model [7]. The role of the Asset Manager is played by the Asset Management department, which is partly centralized and partly decentralized. For communication within the Asset Management department and with the Service Provider, so called guidelines are used. Therefore, the Asset Management department of Essent Netwerk B.V. and KEMA together developed a “Cable Loading Guideline”. The development of this guideline was carried out by a working group, coordinated by a representative of the centralized parts of the Asset Management department. Nevertheless, representatives from the decentralized or regional Asset Management subdepartments were heavily involved in order to ensure the practical applicability of the guideline.

The main tasks of the working group were to:

- Gather general information with respect to the topic of cable rating and thermal calculations in order to provide the necessary theoretical background.
- Use this information to identify the various factors that determine the rating of a given cable in a certain environment.
- Assess whether the information needed to evaluate each of the relevant factors was readily available for the network planners or not.
- If not, develop a pragmatic approach to handle such a factor in the determination of a cable’s rating.
- Draw up a “Cable Loading Guideline” to be used in routine network planning and operation, summarizing the results of the earlier steps in a practically applicable document.

It turned out that there were quite many factors that affect cable rating but are not easily available for the engineers planning MV networks. For these factors, assumptions were made in order to avoid labor and cost intensive data collection yielding only limited added value. Examples of these are the type and the temperature of the soil, the mutual distance between the individual cables of circuits consisting of single core cables.

Outline of Guideline

The maximum cable loading that is allowed by Essent Netwerk B.V. is limited by the occurrence of soil dehydration. This should be prevented, because it can lead to a permanent change of soil properties that increases its thermal resistance and thus reduces the rating of the cable. Soil dehydration is assumed to occur at a cable sheath temperature of 45ºC. Thus, cable ratings are chosen in such a way that the cable sheath temperature does not exceed this value.

Essent Netwerk’s “Cable Loading Guideline” is based on the following equation:

$$I_{max,equal\_loading} = I_{nom} * P * T * D$$

in which $I_{max,equal\_loading}$ is the peak current that may occur in (n-1) situations when the cables in the bundle are equally loaded. I_{nom} is the nominal cable loading. P is a correction factor for the number of parallel cables (only for MV transmission cables, parallel cables do not occur in MV distribution networks) and the thermal resistance of the soil type. T is a correction for the soil temperature, which is only applied in case of MV transmission cables. This factor introduces a difference between a (lower) summer and (higher) winter rating of MV cables, so that either the summer loading or the winter loading can cause a capacity shortage and both must be monitored. For MV distribution cables, a difference between summer and winter rating is of no use, because their peak currents are monitored only twice a year at Essent Netwerk B.V. Finally, D is a factor to incorporate the thermal dynamics of the cable; this factor is determined by the loading of the cable during (n-1) situations in the grid. It is ensured that failures of MV transmission cables are repaired within 24 hours and of MV distribution cables within 72 hours.

The values of D for different loading patterns, cable types and bundle configurations were calculated using the dynamic thermal cable model developed by KEMA. The value of D was calculated by increasing it until the cable current became so high that the cable temperature reached the permissible value of 45º C. When the cables in a MV transmission bundle are not equally loaded, e.g. because a MV/MV-station feedings some MV distribution feeders or a large customer has been inserted in one of the cables, a correction factor is applied to calculate the maximum allowable current. An example of a calculation result is depicted in figure 3.

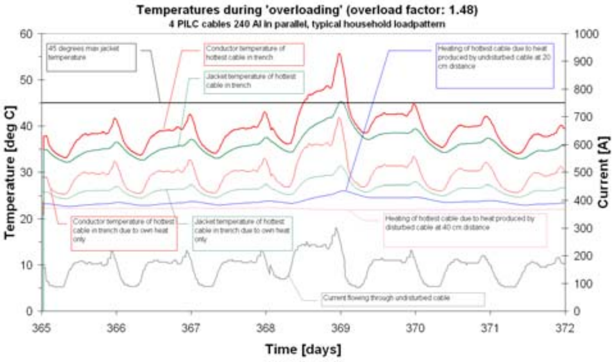

Figure 3. Illustrative calculation result for determining the value of the factor D

IMPLEMENTATION OF THE "CABLE LOADING GUIDELINE"

As can be concluded from the last section, notwithstanding the simplifications, the "Cable Loading Guideline" used by Essent Netwerk B.V. is still quite advanced. The main reason for this is the general observation that the more assets, i.e. MV cables, are to be utilized, the more contingency factors must be taken into account, which results in more extensive data requirements and more complex calculations. Therefore, an adequate implementation of the guideline amongst the employees who are to work with it, is essential. It must be stressed at this place, that it is a general experience of Essent Netwerk B.V. that an adequate implementation of policies and guidelines is key for a successful application of the Asset Management organization model and that this does not only hold for the "Cable Loading Guideline".

The implementation of the "Cable Loading Guideline" was first of all facilitated by the fact that representatives from the decentralized parts of the Asset Management department had cooperated in drawing up the guideline. These employees also served as primary discussion partners concerning the guideline within their subdepartment and when necessary discussed topics with their colleagues both during the formulation of the guideline and after approval. Besides, after the guideline had been approved, a one day conference was organized to inform all employees involved, both from the Asset Management department and from the Service Provider. The number of attendants was about 100. This event proved very successful, first of all to inform all people involved about the principles and application of the new guideline, but also to strengthen the ties between the Asset Manager and the Service Provider and between the geographically decentralized parts of both. Finally, it was clearly communicated at this event whom to address with questions about the guideline so that questions occurring during its application could be answered quickly and easily.

CONCLUSIONS

The subject of this paper was exploiting the thermal behavior of MV cables in routine network planning in order to postpone or avoid investment in MV network reinforcement without (significantly) compromising reliability of supply and/or cable lifetime. It was discussed that due to the thermal dynamics of MV cables on the one hand and the loading pattern and grid operation in The Netherlands on the other, it is possible to temporarily allow a higher cable current than the continuous rating without exceeding the maximum permissible cable temperature.

It was, however, also concluded that the thermal behavior of MV cables can only be exploited in routine network planning when an approach is formulated that can indeed be applied in practice by the employees involved. Therefore, Essent Netwerk B.V. decided to have a "Cable Loading Guideline" formulated by an internal working group supported by KEMA. In the developed guideline, a straightforward approach to determine capacity shortage in MV transmission and distribution networks while taking into account thermal dynamics of a cable was described.

Finally, it was pointed out that an adequate implementation of any guideline, including the developed "Cable Loading Guideline", is essential, particularly in organizations shaped according to the Asset Management organization model. The implementation of the "Cable Loading Guideline" at Essent Netwerk B.V. was described and it was stated that a participative approach in developing guidelines to be applied by decentralized parts of the Asset Manager and by the Service Provider greatly facilitates implementation.

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