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DYNAMIC RATING SYSTEMS IN GENERAL AND IN A HIBRID 150 KV TRANSMISSION SYSTEM

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ABSTRACT

In this paper dynamic rating techniques are described, presented, demonstrated and evaluated. Attention is paid to finding thermal bottlenecks in cable circuits, to on-line and off-line applications and to the relation between thermal models and measurements. The possibilities of on-line dynamic rating systems is demonstrated with a pilot project at utility NUON in which a 150 kV connection consisting of an oil filled power cable and an overhead line in series is set up, deployed and verified against real practice. Throughout the paper, attention is paid to the practical application of modern techniques to optimally utilise the possibilities of connections.

KEYWORDS

Dynamic rating, ampacity, thermal bottleneck, hotspot, optimal usage, asset management.

1. INTRODUCTION

The rating of power cables is a very important subject for utilities. After all, power cables are installed to transport power from one place to another in a reliable way. As the transported power is the product of voltage and current, and the voltage is both fixed by the network and tested during installation / commissioning, the current rating of power cables is of great importance.

Utilities have the difficult task to manage many cables, lasting decades. As the ampacity (current carrying capacity) of a cable is usually only determined at the beginning of the lifetime of a cable circuit, ampacity calculations, including their assumptions may have been performed decades ago. In those days, the use of an assumed set of soil conditions and the use of stationary (sometimes simplified) calculations were much more common than nowadays, now that there are ways to determine soil thermal parameters by soil surveys and improved dynamic calculation methods.

With modern techniques, a re-assesment of the ampacity of underground power cables is often advantageous. The thermal inertness of the soil can be used to transport more current than the stationary maximum (the IEC 60287 continuous current rating [1]) without thermally overloading the cable circuit. Techniques are becoming available to determine the actual thermal bottleneck of cable circuits, so that calculations can be focused on the weakest part of the chain [2].

While on the one hand more techniques to assess the true ampacity of power cables are becoming available, on the other hand utilities are forced more and more to transport energy in the most cost-effective way. As nowadays installing a new cable circuit in an increasingly urbanised environment implies increasing permitting times, increasing numbers of HDD crossings and in general increasingly difficult installation procedures, the capital investments in cable circuits increase. If utilities can invest 'just-in-time' in the network because new techniques determining the cable ampacity are used without introducing unmanageable risks at the same time, this is a very interesting way forward.

An example of what can be realised with the techniques mentioned is described in this paper: the realisation of a dynamic rating system of a 150 kV hybrid connection consisting of an oil filled cable and an overhead line, both without direct temperature measurements as is the usual case with power cables [3]. However, this paper also focuses on new techniques and principles regarding dynamic rating, to be specified in paragraphs 3 and 8.

2. THERMAL BOTTLENECK OR HOTSPOT ?

Regarding definitions, it is proposed to use the term *"thermal bottleneck"* for that location in a cable route that really limits the cable's ampacity. A *"thermal bottleneck"* is different from a *"hotspot"*, which is only a location in a cable route with an elevated temperature at a certain time instant.

Example: suppose there is a cable route, partly installed in soil with bad thermal properties and crossing a hot pipe in soil with very good thermal properties. With low loading, the hot pipe will be a hotspot in the cable route, but it will not per definition be the thermal bottleneck. The thermal bottleneck in this situation may very well be the situation with the soil with bad thermal properties, which was not the earlier defined hotspot.

3. APPLICATION OF DYNAMIC RATING

Performing dynamic rating techniques on power cables has many forms and related benefits. In this paragraph a number of application possibilities that have already been applied in practice will be demonstrated and secondly, economic drivers for introducing dynamic rating techniques are mentioned.

3.1. Technical possibilities

Dynamic rating calculations can be performed for all power cables as long as the current flowing through the cables can be monitored or estimated. From gained experience, three important areas of application can be identified:

On-line dynamic rating

Firstly, there is the possibility to perform dynamic rating applications on line to provide an as accurate as possible insight in the limitations on cable loading. Software has been developed that is capable of calculating the future loading possibilities of underground power cables, overhead lines and power transformers which displays this information in the control room of a utility [3-5]. The latter can either be done on a standalone PC or directly in an EMS system based on information delivered by the dynamic rating system (see figure 1). Because in the control room environment, decisions have to be taken quickly, a simple user interface is developed, showing on-line the times to overload for a certain connection in the grid. Such a system was realised also in the pilot project described in this article, see paragraphs 4, 5 and 6.

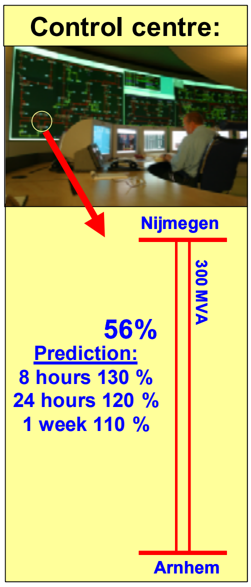

Figure 1: with on-line dynamic rating, loading possibilities can be made available trough the EMS in a simple way.

Off-line dynamic rating

Secondly, dynamic rating calculations can also be performed for groups of power cables, for example groups of medium voltage cables. Grouping of cables has to be performed carefully as changes in the installation details may have an important impact on the cable rating. However, performing dynamic rating calculations for groups of cables may lead to a more optimal usage of power cables in that particular group, just because the dynamics of a situation are added. The calculations are usually performed for certain scenarios: a fault giving rise to an increased loading during maximally 24 hours for example. These situations cannot be modelled with IEC 60287, or with IEC 60853 because usually the cables are loaded dynamically rather than stationary. See for an example of an off-line scenario analysis, figure 2 in which a bundle of 4 parallel MV PILC cables with a spacing of 20 cm and a dynamic daily loading experiences a fault which is always repaired within 24 hours. The figure shows the maximum possible loading trough the cable bundle without crossing a temperature limitation, which was set on 45 ºC cable jacket temperature in this example. Reference [6] gives an example of a utility developing dynamic rating calculation tools for the medium voltage network in the engineering guidelines.

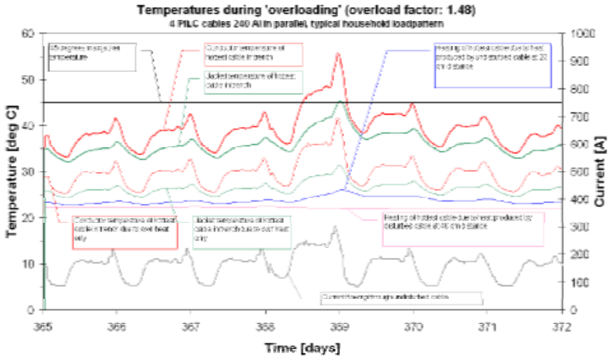

Figure 2: Result of an off line dynamic rating study, leading to the maximum loading possibility in a certain scenario.

Dynamic rating calculations together with temperature measurements

Thirdly, dynamic rating calculations can be used together with temperature measurements. Temperature measurements of power cables using thermocouples or glass fibres are common techniques, and it is very interesting to relate these measurements to dynamic calculations. This has different advantages:

- **Verification**. By measuring, one can check dynamic rating models. When dynamic rating model and temperature measurements match well for a longer period of time, the models can be used to predict the future loading possibilities as described earlier in this paper. From experiences so far, measurement periods of 3 weeks with a loading as high as possible for a utility seem adequate. See for a verification result figure 3 and paragraph 6.

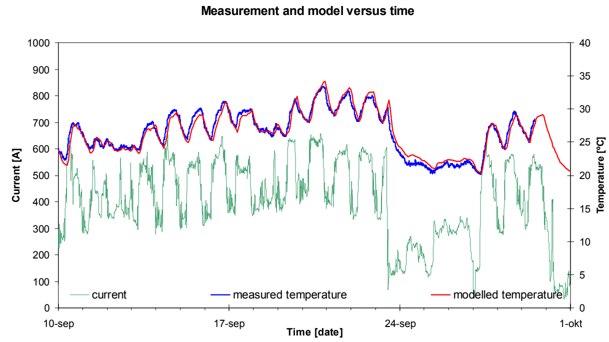

Figure 4: Verification of a modeled temperature (red) with a measured temperature (blue). In green the current is shown

- **Test after commissioning**. When a verified model is available, it is possible to check whether the cable can reach its designed ampacity or not, by using the model. The interesting point is, as already mentioned in the introduction, that this is one of the first possibilities to check the current carrying capacity of power cables, something very important for utilities and enabling checking the assumptions made in the design and engineering phases of realisation projects. As one needs current flowing through a cable to perform this 'test', this idea can end up with the definition of a 'test (directly) after commissioning'.
- **Learning**. Although still not many cables have integrated or remote glass fibres for temperature measurements, these cables can be used to learn something that may be applicable to all cables.

Checking temperature measurements and relating the results with terrain artefacts enables to perform increasingly intelligent cable route surveys to pinpoint the thermal bottleneck. Although not every variation in temperature can be explained easily and measurement artefacts (noise levels, spatial resolution, thermal response to glass fibre welds) disturb measurements up to a certain level, many temperature artefacts can be related to terrain and installation details and can be used to form 'knowledge rules'. These knowledge rules can be used also in situations with similar installation types but with cables without glass fibres. See for an example figure 4.

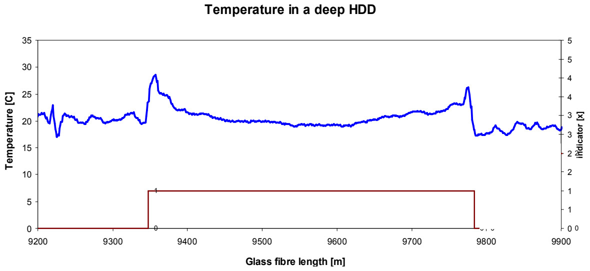

Figure 4: A temperature recording (with glass fibre) of a cable in a deep and long directional drilling. Typical temperature peaks can be seen at the ends of the drilling.

3.2. Economic benefits

Dynamic rating systems are valuable for utilities because they enable optimal utilisation of power cables. What is needed is software, which can be made robust, user friendly and specific for a utility or for an application. The dynamic models only need to be periodically checked using temperature measurements by thermocouple or glass fibres.

Dynamic rating techniques will allow cables to be loaded above their stationary rating for a limited period of time, depending on the cable, installation and operation details. This results in the following economic benefits for utilities:

- **Just-in-time investment** as described in the introduction.
- **Increasing network flexibility**. Energy transport trough the network is increasingly less predictable because of less predictable generation (the exact location of energy generation depends on the market request, increasing amounts of wind energy, decentralised generation) and increasingly mobile clients (e.g. datahouses). This calls for a network capable of handling quickly changing energy transports.
- **Better knowledge** of the historic loading of cables and with that, a better knowledge of possible degradation mechanisms acting in the network
- **More possibilities to solve network contingencies**. When the true loading possibilities are known in the control room, the operator can use the system optimally to prevent switching off clients in the case of a network contingency.
- **A more intelligent way of network operation**. When the network consists of cables with dynamic rating systems predicting the future loading possibilities, better options for operation the network may become available, decreasing costs. See paragraph 8.

4. DYNAMIC RATING PILOT PROJECT

A dynamic rating pilot project was set up at Nuon to identify the benefits of dynamic rating as an innovative system to optimise the utilisation of cable systems [3]. The pilot project has been applied to the 150kV connection Diemen – Venserweg in the vicinity of Amsterdam. This connection consists of a double circuit and is one of the backbone feeders of the Amsterdam area. Each circuit consists of an oil filled power cable, an overhead line and again an oil filled power cable in series, both with their own thermal restrictions (see figure 5 for a schematic representation of the circuit under consideration).

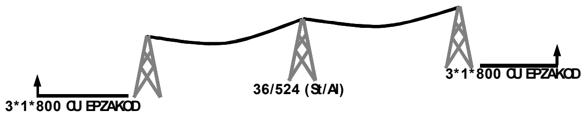

Figure 5: A schematic representation of the circuit under consideration.

For investment planning, studies are performed on a yearly basis in order to point out overloaded power connections in the grid. The national power regulator requires that the 150kV grid must be fail-safe under the following emergency conditions:

- A breakdown in the 150kV grid (the "N-1" condition)
- A breakdown during maintenance in the 150kV grid (the "N-2" condition)

From these requirements, the connection Diemen – Venserweg emerged as a high loaded connection during emergency conditions. Both this expected overloading and the differences in thermal behaviour of an overhead line and an underground power cable were the reasons that the connection Diemen – Venserweg was selected to be subject to a dynamic rating system within this pilot project.

5. THERMAL MODEL

The connection was investigated in detail to determine the thermal bottleneck in the cable circuit. The oil filled cable circuit did not contain a glass fibre to ease this search. Therefore, the circuit configuration and environment were studied in detail. Also based on what was learned from 10 years of glass fibre temperature measurements (what has more impact: bad soil or a parallel cable? Also see paragraph 3.1), the thermal bottleneck was identified to be a dyke crossing in the cable route. Based on this thermal bottleneck, a dynamic thermal model of the power cable was set up. A second thermal model was set up for the overhead line, which has a 'moving' hotspot depending on the weather conditions. The thermal models are discussed in the next two subparagraphs.

5.1. Thermal model of the power cable

In the dynamic thermal model of the power cable under consideration, the cable is represented as a ladder network of thermal resistances and capacitances, resulting in a set of equivalent electric network equations. These models are closely related to the relations as described in IEC 60853 [7], although the model used here is able to perform on-line calculations (see paragraph 3.1, item 1).

The actual thermal situation of the thermal bottleneck in the cable is calculated. The on-line data used for this is the actual load delivered by the EMS system. Also the undisturbed soil temperature near the cable circuit is taken into account as a continuously varying parameter. This undisturbed soil temperature is not measured in this pilot project, but is deduced from an investigation towards both the theoretical behaviour and undisturbed temperature measurements in the Netherlands. The resulting curve may be changed by the user or may be replaced by an actual measurement in future.

Modelling the thermal bottleneck found was performed by using available data on the situation, and realistic, but worst case approximations where necessary. This also leads to a certain safety margin in the final results. In a later stage, the models that have been set up were verified by temperature measurements in practice. For this, see paragraph 6.

5.2. Thermal model of the overhead line

The dynamics of an overhead line do not result from thermal inertness as is the case with underground cables. The temperature of the overhead line quickly responds to changes in the loading and in the weather, with time constants in the order of tens of minutes. However, changes in the weather have a large impact on the rating of an overhead line and are therefore very interesting. In many countries it is common to have a summer and a winter rating of an overhead line. In the dynamic rating system, the same idea is used, but on a much finer timescale.

The model used for thermal calculations is described in [8,9]. The model has already been subject to detailed investigations and verifications with measurements [10].

The model is operated based on load and weather data. The weather data is provided once every day and consists of measured data regarding the weather of the day before and the forecasted weather for the next five days. The weather is measured close to the location of the overhead line. The actual thermal situation of the overhead line is calculated based on the *forecasted weather data* and the actual load on the line. About 24 hours after such a calculation, the calculation is repeated with *measured weather data* rather than *forecasted weather data*. This enables assessing the quality of the forecasted weather data, and the influence of using forecasted instead of measured weather data on the actual thermal situation of the overhead line. Based on this information, it could be decided whether an extra safety margin should be included in the calculations because forecasted rather than measured weather data is used.

6. MODEL VERIFICATION

After the dynamic rating system was installed, the dynamic rating model for the power cable was verified with a thermocouple. In a later stage, also the overhead line thermal model will be verified using a direct temperature measurement on the overhead line conductor.

During a period of several months the temperature of the cable and the soil in vicinity of the hotspot has been measured. In this period of time several ‘emergency situations’ were simulated by switching off the parallel connection. This enabled recording the heating and cooling of the cable jacket and the surrounding soil.

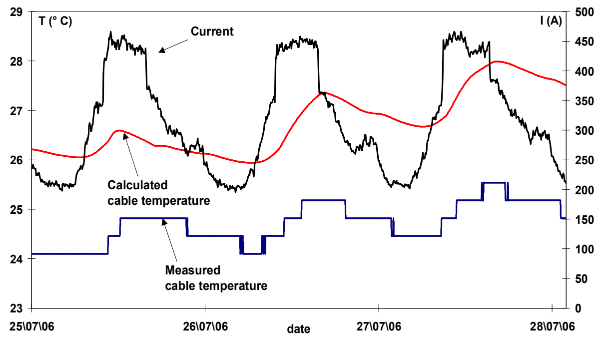

Figure 6: A comparison of the modelled cable (jacket) temperature with the measured cable temperature.

One of the model verifications is presented in figure 6. The discrete character of the measured curve in figure 6 is due to a inaccurate adjustment to the A/D converter. However, from this figure it can be seen that the real-time recording of the cable jacket temperature is in shape equal to the calculated jacket temperature. The measured temperature is somewhat lower than the calculated temperature due to the worst case approximated undisturbed soil temperature (see paragraph 5.1). The steepness of both curves is almost identical in warming-up and cooling-down periods.

7. COLLECTED EXPERIENCE

Within the pilot project, the following major experiences were reached:

- Deploying dynamic rating systems enables increasing circuit loading without exceeding the thermal limits stated. With these systems, higher loads can be transported during emergency situations and financial benefits may be gained by investing just-in-time and by planning maintenance periods efficiently.
- The dynamic rating system has been based on dynamic models rather than on measurements. This is an advantage in the usability, reliability and pricing of such a system.
- Preparatory studies to find the thermal bottleneck in a cable circuit and to evaluate the engineered rating of the cable circuit have a high added value and need to be done before a dynamic rating system is installed.
- An in-depth site and soil survey was necessary to find the hotspot because no glass fibre was present in the transmission connection. For new cable systems one has the choice to integrate glass fibres against relatively low cost. Since glass fibres facilitate the finding of hotspots to a large extend, integrating glass fibres for temperature measurements in new connections is worthwhile.
- Creating a basis in the organisation for innovative techniques as dynamic rating systems needs broad appreciation.
- The model was found to correspond to reality rather good after the model was deployed.

8. REMAINING CHALLENGES

Regarding the application of dynamic rating, there is a very interesting future challenge to be addressed. This is to perform a dynamic rating pilot project for a number of power cables or overhead lines, forming a ring or a mazed grid. When in such a ring or mazed grid the future loading possibilities of all cables and overhead lines can be calculated with dynamic rating systems, another way of network operation can be made available. This enables much more than now a kind of network operation reflecting the business values of a utility: One can try to optimise emergency loading possibilities in the network to prevent switching off clients if a failure occurs, One can decide to load certain connections higher in order to spare other cables and so to keep the network (theoretical) thermal degradation of all connections equal, One can try to lower energy losses by keeping the temperature of cables as low as possible, using the thermal inertness of the systems optimally, et cetera.

Besides exploring these new possibilities, it is very important to keep learning knowledge rules (see paragraph 3.1) from relating measurements with thermal models and thereby improving both cable circuit design and engineering practices and improving finding and describing thermal bottlenecks in underground cables.

A third remaining challenge is to relate the historic thermal load to the cable condition and the remaining life. However, as the subject of degradation and remaining life is very difficult, this topic will probably remain a challenge for the years to come.

Predominantly within Nuon, the following challenges remain to be explored:
- A convincing glass fibre measurement
- A solution for a standalone thermocouple measurement with data functionality

9. CONCLUSIONS

Dynamic rating is a useful technology to optimize operating management of a transmission system, without exceeding maximum temperatures, both from a technical and an economical point of view.

A pilot project is an important tool to collect experience. The pilot project has to be based on an advanced model representing the thermal behaviour of the relevant components.

Interesting elements in the pilot project are in particular: the verification of the thermal model and site /soil surveys to locate thermal bottlenecks.

Finally the Dynamic Rating technology has the following future challenges:
- Application for mazed networks
- Development and application of knowledge rules
- Application of remaining life management

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