FULL-SCALE CASE STUDY OF A ROAD CROSSING THERMAL BOTTLENECK IN A BURIED MV CABLE INSTALLATION

Espen EBERG
SINTEF Energy Research - Norway
Espen.Eberg@sintef.no

Kåre ESPELAND
REN AS
Kare@ren.no

Svein M. HELLESØ
SINTEF Energy Research - Norway
Svein.M.Helleso@sintef.no

Sverre HVIDSTEN
Norway SINTEF Energy Research - Norway
Sverre.Hvidsten@sintef.no

ABSTRACT

Infrastructures such as road crossings, are often limiting the ampacity of a cable link due to poor thermal properties. In order to fully utilize the true loading capacity of the cable, thermal modelling with correct input parameters should be applied. In this work, a full scale artificial road crossing have been constructed and characterized, and temperature measurements have been compared with calculations performed according to IEC 60287 and finite-element analysis (FEA). It was found that calculations according to IEC provide a good fit to measured temperature profiles by adjusting the unknown mean thermal resistivity of the material layers outside the pipe. The thermal properties of road construction materials can be challenging to measure, and in order to provide accurate ampacity calculations further work should be focused on this.

INTRODUCTION

There is an increased focus on utilization and demand for security-of-supply in all parts of electric power transmission and distribution systems. For distribution grid system operators (DSOs) this manifests as a demand for more accurate calculation of the current carrying capacity (ampacity) of the circuits, in order to utilize present infrastructure, and optimize future investments.

One of the limiting factors for electric power distribution circuits is thermal overload, where the conductor exceeds a limiting temperature where thermal expansion becomes problematic, and finally the encapsulating insulation systems deteriorates and results in short term breakdown or decreased lifetime [1].

For buried cables, the thermal resistivity of the surrounding soil and bedding materials can account for up to 70% of the temperature rise of the conductor [2, 3]. Hence, much effort have been put into characterizing and optimizing bedding materials. Especially the moisture content in bedding materials have caught interest, since the thermal resistivity increases by a factor of 3 when the moisture content decreases from a normal moisture level (5-10 %) to dry state (0 %) [4]. Seasonal variations in precipitation and seepage, in addition to temperature variations, will thus alter the thermal properties of the backfill materials during the year, and hence also the ampacity of the cable link.

In the distribution grid, buried cables often interfere with other infrastructure, e.g. road crossings, and the cables are often laid in pipes or ducts for protection. Regulations from road authorities or similar can also put restrictions on what type of bedding materials than can be used. In such cases, the locally increased thermal resistivity lead to additional heating of the cable. A calculated example gives an ampacity reduction factor of 40% [5], hence such thermal bottlenecks (TBs) is often the limiting factor for ampacity of the distribution circuit. There is a varying practice how this is taken into account by grid owners, as very few derate the circuit according to the geometry of the TB [5]. Recent recommendations state the TBs should be taken into account if they are longer than 5 meters [3].

Cable laying under and crossing paved roads are common TBs along distribution cable routes, and accurate rating of these will in many cases make it possible to increase the load - or assure that overheating is avoided in case the TB have not been accounted for in the rating calculations.

The main purpose of this paper is to perform initial measurements on a common TB, i.e. road crossing, in order to investigate relevant parameters and their natural variation for accurate ampacity calculations. Further work will focus on local heat transport in pipes and estimation of thermal properties in coarse bedding materials.

EXPERIMENTAL

Road crossing geometry

A road crossing was constructed according to the Norwegian Public Roads Administration (NPRA) standard for road construction and interfering infrastructure [6]: A 24 kV XLPE cable with 50 mm^2 cross section Al conductor was placed in a 110 mm PE pipe 109 cm below ground level. A protection layer of 4-16 mm gravel surrounds the pipe. The main body consist of coarse 22-63 mm gravel, with a base layer of 0-16 mm

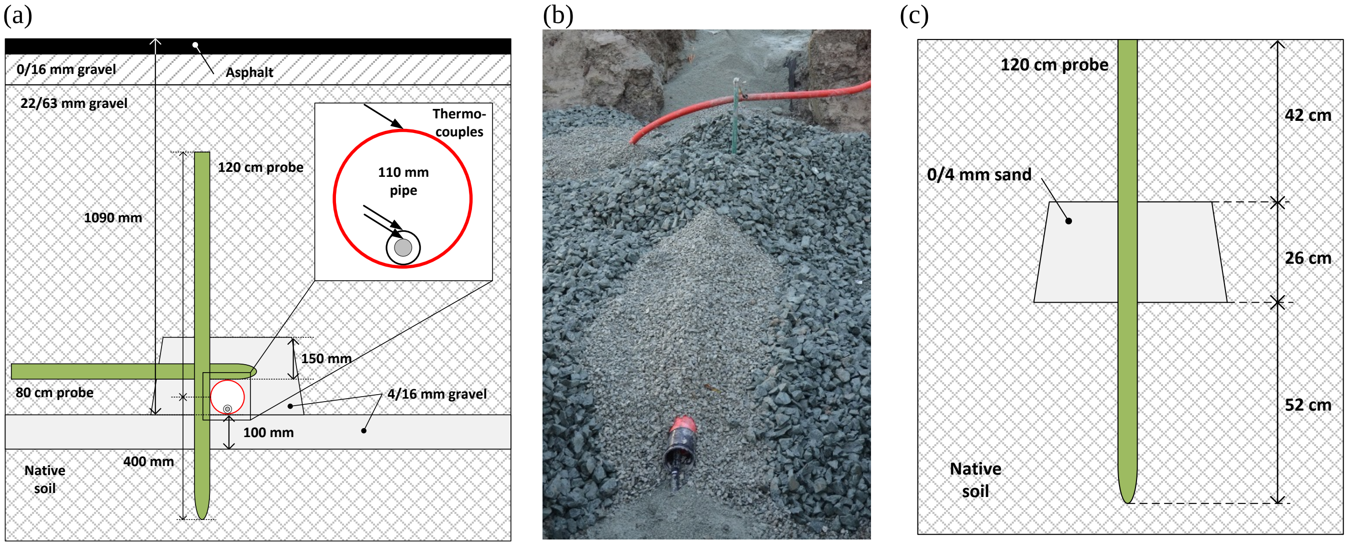

Figure 1 (a): Schematic of road crossing. (b): Image of the actual road crossing during construction (not completed). (c) Trench for reference temperature and moisture

sand beneath the asphalt on top. The geometry is illustrated in Figure 1, and an image of the road crossing during construction is shown in Figure 1 (b). The projected area of the artificial road is 6 x 6.5 m^2, i.e. the length of the TB is six meters.

For temperature monitoring in the cable conductor, jacket and outside PE pipe, K-element thermocouples was used. Temperature and moisture profiles were measured using *EnviroPro* probes in the horizontal (80 cm) and vertical (120 cm) directions as shown in Figure 1 (a).

Reference trench geometry and climate monitoring

In order to measure reference temperature and moisture profiles, a 120 cm *EnviroPro* probe was placed vertically in a reference cable trench, but without any cable installed, as illustrated in Figure 1 (c). The trench was constructed according to Norwegian guideline REN 9000 [7], also in agreement with IEC 60287 3-1 [8].

The bedding material for the reference trench was 0/4 mm well-graded sand from crushed rock, and the native soil was clayey soil. All bedding materials for both road crossing and reference trench came from a local quarry outside Trondheim, Norway, with gabbro as major mineral type and a measured particle density of 3.02 g/cm^3.

A *Vaisala WXT520 Weather Transmitter* was installed six meters above the ground on a pole at the site for monitoring of air temperature and precipitation.

In Figure 2 (a) the daily mean temperatures in air, in the ground 70 cm below the surface in the reference trench, and in the ground 109 cm below the surface in the road crossing 70 cm horizontally displaced from the pipe, are shown. In order to validate calculations, a period of one week is chosen as reference data where the daily mean air and soil temperature have been stable for three weeks prior to this. The chosen interval is marked in Figure 2 (a) as measurement period, and the mean ambient (air) temperature is set to -1 °C.

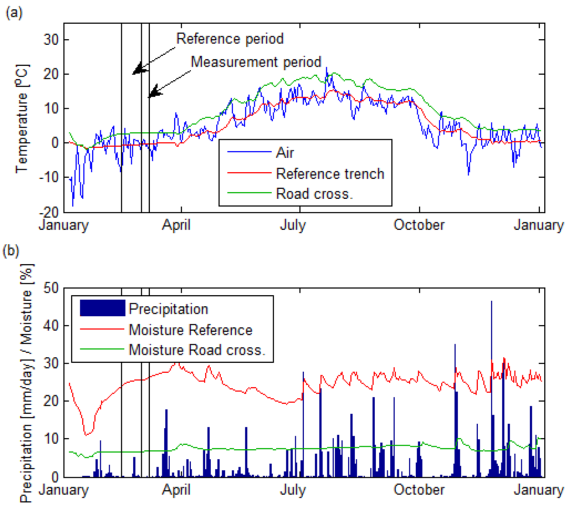

Figure 2: Daily mean (a) temperatures and (b) precipitation and moisture levels.

In Figure 2 (b), daily accumulated precipitation, daily mean moisture content in the reference trench, and in the road crossing close to the pipe, is shown for a period of one year. Characteristic values of moisture content is summarized in Table 1.

Table 1: Moisture levels in reference trench and road crossing.

	Min	*Max*	μ	σ
Reference trench	11 %	36 %	25 %	4 %
Road crossing	5 %	10 %	7 %	1%

It can be seen that there is a close correspondence between the precipitation and moisture content in the reference trench, where the moisture level varies between 11% and 36% over one year. The moisture content in the road crossing follows the same trend, but the base level is lower and the variation is significantly smaller. It should be noted that the moisture sensors are calibrated for fine sands, and coarse materials with air pockets and grains at the same order of magnitude as the measurement volume can give anomalous readings. The crushed rock is used for road construction for its draining capacity; hence the low and stable moisture content as measured is to be expected.

CALCULATIONS

Ampacity calculations for the road crossing was undertaken following IEC 60287 1-1 [9] and 2-1 [10]. As initial (dry) thermal resistivity ρ_s = 2 (K·m)/W was chosen, based on laboratory measurements of coarse base-course materials from literature [11].

Finite-element analysis (FEA) was performed using COMSOL Multiphysics, with a two-dimensional geometry as illustrated in Figure 1 (a). The cable was modeled with conductor, insulation, screen and outer sheath. The cable was positioned in the bottom in the pipe but with a small gap between the cable and pipe wall, thus solid-solid conduction in the narrow mechanical contact area was not included. The pipe was then surrounded by the layers that represents the road, and with the native soil beneath and on the sides of the road.

The thermal model for solid parts consisted of conduction, while the thermal model for the air-filled pipe included conduction, convection and radiation effects. The convection was modeled as a temperature-dependent buoyancy force that set up a natural convective flow inside the pipe. The radiation model considered internal surface-to-surface radiation with a hemicube method, assuming an emissivity factor of 1.0 for both the cable outer surface and pipe inner surface.

The electrical current distribution and resultant heating was modelled using a Magnetic Fields formulation, with 50 Hz excitation.

The temperature at the surface was set to a fixed value, while the other boundaries was assumed to be insulated. A vertical symmetric line through the center of the pipe and cable was imposed to reduce the size of the model and improve the convergence when solving the model.

The length of the road crossing was six meters; hence longitudinal thermal conduction could be neglected according to previous FEA calculations on a similar geometry [12].

RESULTS AND DISCUSSION

IEC 60287 calculations

With an ambient temperature of 15 ˚C and conductor temperature 90 ˚C, the ampacity for the road crossing is found to be 180 A, which was the target load for the experimental setup. Using an ambient temperature of -1 ˚C, as found for the chosen measurement period, the ampacity is 201 A. With an applied current in the circuit of 182 A, the calculated conductor temperature is 68 ˚C with -1 ˚C ambient temperature.

Finite-element analysis

The results from the FEA shows that due to the radiation the temperature of the pipe is highest at the bottom of the pipe. The convections sets up a hot flow of air that give a local maximum in temperature at the top of the pipe.

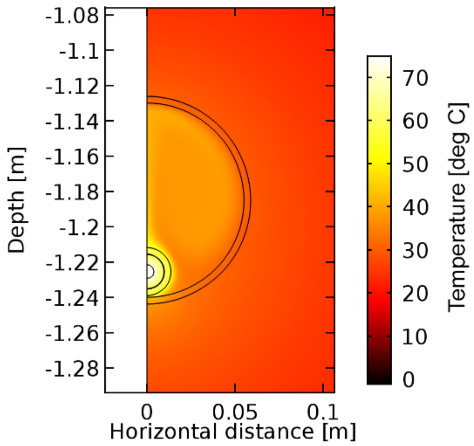

Figure 3: Heat map from FEA calculations.

Calculated horizontal and vertical temperature profiles are given in Figure 4.

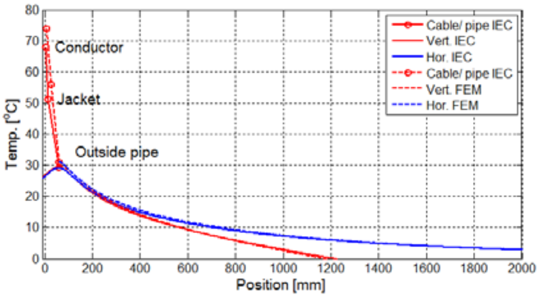

Figure 4: Horizontal and vertical temperature profiles calculated according to IEC (solid lines) and FEA (dotted lines).

Table 2: Comparison of temperatures (°C) calculated by IEC 60287 and FEA.

	Conductor	*Jacket*	*Pipe*
IEC 60287	74	51	31
FEA	68	56	29
$\Delta\theta$	6	4	2

There is a significant difference between the calculated conductor temperature for IEC and FEA. The FEA calculations should in principle be an accurate representation of the heat transfer phenomenon. The IEC formulation on the other hand, is a semi-empirical expression that tries to represent experimental results. However, the semi-empirical expressions might contain some discrepancy that means that it does not represent the actual heat transfer phenomenon. A possible explanation is that the neglected solid-solid thermal conduction has to be included to give an accurate result, and should be further investigated.

Road crossing measurements

In Figure 5 the measured vertical and horizontal temperature profiles are compared to calculations according to IEC 60287, and in Table 3 temperature differences inside and on the pipe are summarized. The calculated temperatures outside the pipe is offset according to the probe positions in Figure 1.

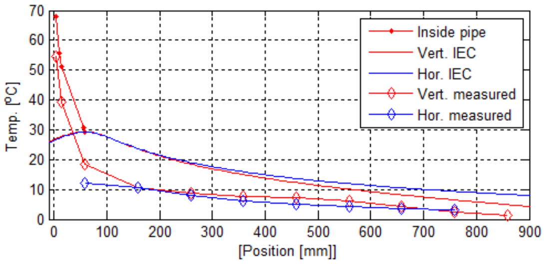

Figure 5: Measured and initially calculated temperature profiles.

Table 3: Temperature (°C) differences between measurement and IEC 60287 calculation

	Conductor	*Serving*	*Pipe (outside)*
IEC 60287	68.0	51.1	29.3
Measured	54.6	39.3	18.3
$\Delta\theta$	13.5	11.8	11.0

For the measured vertical temperature profile, the temperature reading on the pipe wall is taken from the thermocouple attached to the top of the pipe.

The calculated temperatures inside and on the surface of the pipe, for the given load of 182 A, generally gives too high temperatures when compared to the measured values and thus a conservative estimate of the ampacity of the circuit. Outside the pipe, the difference between measured and calculated values decreases as the distance to pipe increases.

A likely explanation for the higher calculated temperatures is a lower thermal resistivity in the road crossing than initially assumed. The IEC calculations were thus recalculated with lower thermal resistivity until a best fit to the measured temperature profile was attained.

In Figure 6 and Table 4 the same measured temperature profiles are compared to temperature profiles calculated according to IEC 60287, but with ρ_s = 1.2 (K·m)/W. It can be seen that the difference is negligible for measured temperatures at all positions, both in cable, pipe and surrounding gravel. The only discrepancy observed is the temperature value at the top and the tube, taken from the horizontal laying probe. The horizontal probe reads a 6 °C lower temperature compared to the thermocouple attached to the top of the pipe. The temperature sensors are placed with 10 cm intervals on one side along the probe. It is thus unlikely that the specific sensor on the probe will be positioned exactly at, and in contact with, the pipe, resulting in a lower temperature reading from the probe.

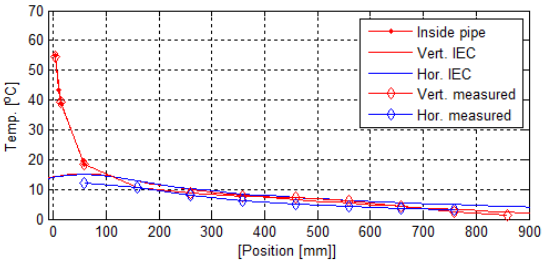

Figure 6: Measured and calculated temperature profiles with ρ_s =1.2 (K·m)/W.

Table 4: Temperature differences (°C) between measurement and IEC 60287 calculation

	Conductor	*Serving*	*Pipe (outside)*
IEC 60287	55	39.0	18.3
Measured	54.6	39.3	18.3
$\Delta\theta$	0.4	-0.3	0.0

A thermal resistivity of 1.2 (K·m)/W is low for a coarse gravel with good draining properties. For gabbro, the tabular value of mineral thermal resistivity is 0.45 (K·m)/W. Applying an empirical model for thermal resistivity in soils and building materials [4], with a dry density of 2.5 g/cm^3 and porosity of 0.17 a thermal resistivity of 1.2 (K·m)/W is attained. This value of density is high, but not unrealistic, as lower porosity have been achieved for similar materials under laboratory conditions [11]. On the other hand, a thermal resistivity of 1.2 (K·m)/W and a moisture content of 5% the model gives a dry density of 1.75 g/cm^3, and a porosity of 0.42, which is very low and only achieved when compacting is not applied. Due to the large particle size, large test cells are necessary to measure the thermal resistivity of such materials, and were unavailable at the time.

Also, the road crossing has a layered structure giving an inhomogeneous soil thermal resistivity: At the surface, one meter above the cable, there is a layer with a well-graded base material and asphalt. This layer is expected to have a lower resistivity than the gravel, but due to the long distance from the cable it can be neglected. Below the cable (and pipe), there is only a 10 cm layer of gravel above the native soil. At the test site the native soil is clayey, and measured moisture content in native soil at 1.2 m depth is in the range 35% - 40%. The thermal resistivity of native soil beneath is thus probably significantly lower than the thermal resistivity of the gravel in close proximity to the cable/pipe, which can contribute in reducing the effective thermal resistivity seen by the pipe. It is possible to take this into account using conformal transformation method as described in Ref. [13], but is not applied as neither the accurate values of thermal resistivity in gravel or native soil have yet been measured.

CONCLUSIONS

A full-scale artificial road crossing was constructed and conventional IEC and FEA ampacity calculations was compared with measurements of temperature profiles in ground, with the purpose of investigating the accuracy of such calculations and effect of uncertainty in thermal properties of the cable link.

The main findings are:

- There is a good correspondence between IEC and FEA calculations, although the eccentric cable position in the pipe probably results in an overestimation of conductor temperature.
- By adjusting the thermal resistivity of the soil, a good temperature distribution fit between IEC calculations and measurements is obtained.
- The effect of inhomogeneous thermal resistivity, i.e. layers with different thermal resistivity, is not taken into account IEC calculations. In this case, the native soils is likely to have a low (wet) thermal resistivity which give a negative contribution to the thermal resistivity used in IEC calculations.
- In order to take advantage of the possibilities in FEA for inhomogeneous thermal resistivity, good estimates for the applied backfill materials is a necessity. This can be done either by developing measuring techniques for thermal resistivity or refining empirical models and find estimates indirectly. For coarse gravels, and other materials that are challenging to characterize, such a method would be of great advantage.

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