# DEVELOPMENT OF A WEB-BASED USER-FRIENDLY CABLE AMPACITY CALCULATION TOOL

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## *ABSTRACT*

*A prototype of a web-based tool for ampacity calculations has been developed using a commercial finite-element analysis (FEA) software with server functionality. Users can access the tool by an intuitive graphical user interface in a web browser. Comparison of FEA models, implemented in the tool, to IEC 60287 calculations and measurements from a full-scale test are presented. Results show good correspondence between the calculated and measured values.*

## INTRODUCTION

There is an increased focus on utilization and security-of-supply of all parts of the electric power system, and for cable circuits this calls for accurate calculation of the ampacity. For critical applications, e.g. mainland connections and wind farms connections, such accurate ampacity calculations will be crucial to avoid down time due to cable failures and to ensure return of investment.

Current practice for ampacity calculations among most Norwegian DSO's is to use tabulated ampacity values provided by the cable manufacturer or the national standard NEN 62.75. In this standard a set of tables constructed in 1975 mainly based on IEC 287 – now IEC 60287 – are presented [1]. Experience have shown that in many cases the tabulated values does not provide the flexibility needed to estimate the actual ampacity for today's cable circuits. This is especially important for thermal bottlenecks, where the geometry of the cable trench can be more complex or differ from the standard layouts presented in the NEN 62.75. The result is that the ampacity of the cable circuit is either too conservatively estimated, or that the thermal bottleneck merely is neglected. These two scenarios give an uncertainty of the real ampacity, that can result in unused current capacity or increased risk of local overheating.

Ampacity calculations applying IEC 60287 [1] is based on a combination of analytical formulas and simplified empirical expressions describing heat generation and dissipation for most cable types and relevant trench geometries. Performing such calculations by hand or in spreadsheets is time-consuming and complicated, especially for cable circuits involving many cables, and is thus seldomly performed by the DSO's.

Computations of ampacity using finite-element analysis (FEA) are becoming more common. One advantage of using FEA is that constraints on cable trench geometries in IEC 60287 does not apply. Comparison of published FEA models to IEC 60287 calculations for buried cables show generally good agreement [2, 3]. For larger, and more complex structures, such as duct banks, increasing discrepancy is found with increasing number of cables. This is due to the simplifications of electromagnetic couplings in the IEC standard.

For cables in pipes, heat transfer in the air gap between cable surface and pipe wall is approximated by empirical relationships in the IEC standard and the Neher-McGrath method [4]. With increased computational power, FEA methods can provide more accurate models if implemented correctly. Examples of this is found in [5] and [6], where heat transfer by conduction, radiation and convection is included in FEA models and provide very accurate results compared to measurements. One challenge with such complex models is the demand for computational resources.

The main purpose of the work has been to develop a user-friendly and flexible FEA models for Norwegian DSOs. The models can be used without needing any previous knowledge on design and implementation of FEA. This work is a continuation of the work presented in [7], where measurements and FEA modelling of a full-scale road crossing with the cable buried in a pipe was performed. Here, comparison of developed FEA models to IEC 60287 calculations and measurements from a full-scale test trench are presented. Also, the implementation of a web-based GUI for the FEA model is presented.

## EXPERIMENTAL

### Full-scale cable trench geometry

For experimental verification of thermal modelling, a 130 m long full-scale cable test trench with a 24 kV XLPE cable with 50 mm$^2$ Al conductor have been installed. The cable layout is outlined in Figure 1 showing four thermal bottlenecks, with detailed parameters given in Table 1: 1) Close laying of three cables, 2) Cable crossing, 3) Road crossing with cable in pipe, and 4) Cable in pipe with inclination, *i.e.* parallel to the ground in a hill. Between the bottlenecks, the cable is buried at 40 cm depth and embedded in 0/4 mm crushed rock. The Road crossing (#3) was constructed according to Norwegian Public Roads Administration (NPRA) standard for road construction and interfering infrastructure [8] and described in [7]. The current was induced in the cable by a current transformer situated inside a container.

## Monitoring

For each bottleneck, temperature and moisture profiles were measured horizontally and vertically from the cable using *EnviroPro* probes with a resolution of 10 cm over a distance of 40 cm to 120 cm. For the bottlenecks with cable in pipe (#3 and #4), thermocouples for temperature measurements was installed in the cable conductor, on the outer sheath and on the pipe walls. This was done near the ends and at the centre of the pipes in the longitudinal direction.

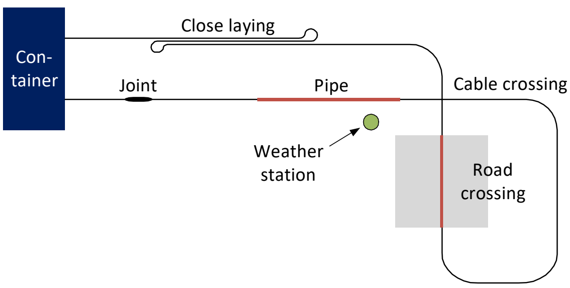


*Figure 1: Test trench cable layout.*

*Table 1: Parameters for thermal bottlenecks*

| *Geometry* | | *Parameters* |
|---|---|---|
| #1 | Close laying | 3 cables parallel<br>10 cm horizontal c-c* distance<br>40 cm laying depth<br>0/4 mm crushed rock |
| #2 | Cable crossing | 2 cables perpendicular<br>10 cm vertical c-c distance<br>40 cm laying depth (top cable)<br>0/4 mm crushed rock |
| #3 | Road crossing | 110 mm PE pipe<br>110 cm laying depth<br>4/16 mm crushed rock |
| #4 | Cable in pipe | 110 mm PE pipe<br>40 cm laying depth<br>0/4 mm crushed rock<br>12% inclination |

*) Center-to-center

The cable was equipped with optical fibres for temperature measurements at the inside of the sheath. An *AP Sensing* distributed temperature sensing (DTS) unit was applied to monitor the longitudinal sheath temperature profile with a spatial resolution of 0.5 m.

For climate monitoring a *Vaisala WXT520 Weather Transmitter* was installed on a pole in the centre of the test site.

# MODELLING

## IEC 60287

Ampacity calculations according to IEC 60287 1-1 [1] and 2-1 [9] was conducted with ambient temperature 15 ºC, and conductor temperature 90 ºC. Soil thermal resistivity was set to $\rho_s$ = 1 K.m/W and $\rho_s$ = 2.5 K.m/W for 0/4 mm and 4/16 mm crushed rock, respectively.

## FEA

All bottlenecks except the cable crossing (#2) were six meters or longer, hence longitudinal heat flow could be neglected [6]. FEA models were made in *COMSOL Multiphysics*, using a two-dimensional geometry. For the road crossing (#2) a three-dimensional geometry was made. The cable was modelled with solid conductor, insulation, hollow cylindrical screen and outer sheath. For directly buried cables (bottlenecks #1 and #2), the heat transfer consisted of conduction. In the air-filled pipes in bottleneck #3 and #4 radiation was included where a surface emissivity factor of 1.0 for both cable and pipe surfaces was used. In order to include convection as a heat transfer mechanism, a heat source representing the convection is subtracted from the heat generated in the cable and added to the upper half of the outside pipe wall [10]. By doing this, heat transfer by convection is included in the model without solving the full fluid flow equations. The temperature at the surface was set to a fixed value, while the other boundaries was assumed to be far away and insulated.

# RESULTS AND DISCUSSION

## Comparison of IEC 60287 and FEA models for directly buried cables

In Table 2 the ampacity for standard trench, for close laying (#1) and cable crossing (#2) is shown for both calculations according to IEC 60287 and FEA models. The relative difference (Δ) is below 1% for these cases, hence deviation between the two calculation methods are negligible for these single core cases.

*Table 2: Ampacity for standard trench, close laying and cable crossing calculated according to IEC 60287 and with FEA, respectively.*

| | *IEC 60287* | *FEA* | *Δ* |
|---|---|---|---|
| *Standard trench* | 262 A | 263 A | 0.4 % |
| *Close laying (#1)* | 212 A | 214 A | 0.9 % |
| *Cable crossing (#2)* | 183 A | 183 A | 0 % |

For further synthetic validation of the FEA models, comparison was made to several IEC 60287 calculations for directly buried cables. In Figure 2 the resulting conductor temperature using the FEA model is shown for single core XLPE cables in trefoil formation as function of Al conductor cross section from 50 mm$^2$ to 2000 mm$^2$ and increasing insulation thickness with voltage class. The current giving 90 ºC conductor temperature according to IEC 60287, were taken from the manufacturer's datasheets for the corresponding cables. The largest deviation found is 6 ºC (7%) and the standard deviation as a measure of overall performance is 3 ºC (3%). It is a tendency that very small and large cross-sections underestimate the temperature compared to IEC 60287, while intermediate cross sections (240 mm$^2$ – 1200 mm$^2$) overestimate the temperature compared to IEC 60287.

For directly buried cables and static conditions, IEC 60287 calculations will generally provide accurate results. Since the surface boundary is isothermal in the FEA models, the good match to IEC calculations are as expected. For shallow buried cables isothermal boundary conditions will give higher ampacity values compared to boundaries where the convective heat flux is used [3]. If such boundaries should be applied in the FEA models, realistic numbers for both the convective heat transfer coefficient and radiative emissivity/ absorption of the ground surface

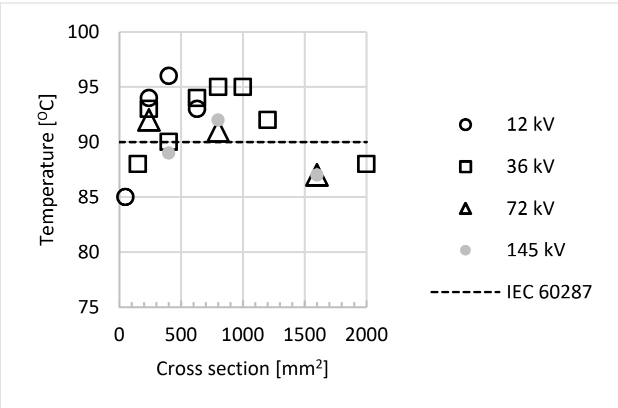


*Figure 2: Resulting conductor temperature for single-core cables in trefoil formation of different conductor cross-sections and insulation thicknesses using from the FEA model when the thermal limit current calculated by IEC60287 is applied.*

should be included. These parameters are highly dependent on the local properties of the surface zone, e.g. fields, agricultural, asphalt or gravel, and meteorological properties such as precipitation and wind speed. Hence for static calculations, an isothermal boundary likely provides sufficient accuracy, but care should be taken for shallow buried cables.

## Experimental verification of FEA models for cables in pipes

In order to validate the FEA model for heat transfer in pipes, deviations between measured and calculated temperature differences were compared. Average temperature differences were calculated based on measurements for a seven-day period in July 2017 with stable soil temperature of 12 ºC at the laying depth. In Table 3, measured and calculated temperature difference between sheath and pipe at top, side and bottom positions are compared for the road crossing (#3). The FEA model slightly overestimates the temperature at the top position by 1 ºC, while underestimates the temperature difference at the sheath – pipe bottom interface by 1.9 ºC. The deviation at the bottom interface is likely due less heat transfer by conduction since the contact area in the physical sheath-pipe interface in the test trench is smaller than in the FEA model.

In Table 4, the measured and calculated temperature difference between the sheath and the side position of the pipe is shown[1] for the cable in pipe (#4). The deviation between the measured and calculated temperature difference is 3.2 ºC. This deviation is larger than experienced for the road crossing. It is suspected that the inclination of the pipe leads to longitudinal convection that can give heat pockets and result in a non-monotonical temperature distribution along the pipe [11].

*Table 3: Measured and calculated temperature differences between sheath and pipe wall at top, side and bottom position for road crossing (#3).*

| | *Measured* | *FEA* | *Δ* |
|---|---|---|---|
| *Sheath – pipe top* | 30.9 ºC | 31.9 ºC | 3% |
| *Sheath – pipe side* | 30.3 ºC | 30.4 ºC | 0% |
| *Sheath – pipe bottom* | 24.9 ºC | 23.0 ºC | - 8% |

*Table 4: Measured and calculated temperature difference between sheath and pipe wall at side position for cable in pipe (#4).*

| | *Measured* | *FEA* | *Δ* |
|---|---|---|---|
| *Sheath – pipe side* | 27.6 ºC | 30.8 ºC | 12% |

[1] Top and bottom temperature sensors not were installed for this bottleneck.

The results from the bottlenecks with cable in pipe indicate that the simplified FEA model [10] provides accurate results for the heat transfer in pipes. For cable circuits in service, coiling of the cable inside the pipe causing the cable to lose contact the pipe surface can lead to an altered temperate distribution. Also, inclination of pipes filled with convective media can give altered temperature distributions. The latter have been appointed as a case where more accurate heat transfer models are required [11].

## INTERFACE FOR FEA MODELS

The main motivation behind establishing the FEA models was to implement these in a flexible calculation tool that would be easily to take into use for utilities. Parallel to the development of the FEA models, a web-based graphical user interface (GUI) was constructed. A work group including members from the Norwegian TSO and major DSOs participated in the work to make the GUI intuitive to utility engineers and planners. A web-page based GUI was implemented using a combination of the built-in graphical tools and Java code in *COMSOL Server* [12]. The FEA model then runs on a dedicated server, and the FEA models are remotely accessible in a web browser.

An example case is shown in Figure 3. The calculation tool is flexible with freedom to customize geometry, cables and material properties. Number and type of cables are chosen in drop-down menus, limited to ten cable groups. Cable geometries can be imported from a predefined library or defined by the user. The position of cables and layers can be arbitrary chosen, and both directly buried cables and cables in pipes can be defined for flat and trefoil formation.

Results from the thermal calculations are provided as a heat map and in tabular form together with *i.a.* magnetic induction, impedance, induced screen current and transmission capacity.

## SUMMARY

A prototype web-based ampacity tool relying on FEA calculations have been presented, and results from the FEA models have been compared to IEC 60287 calculations for directly buried cables and measured values from a full-scale test trench for cables in pipes. The main findings are:

- The deviations between the FEA model and IEC 60287 are negligible for the directly buried cable geometries in the full-scale test trench.
- Comparison between FEA model and IEC 60287 for other cross-sections and insulations thicknesses for directly buried cables gives a maximum deviation of 7% for a conductor temperature of 90 °C according to IEC 60287.

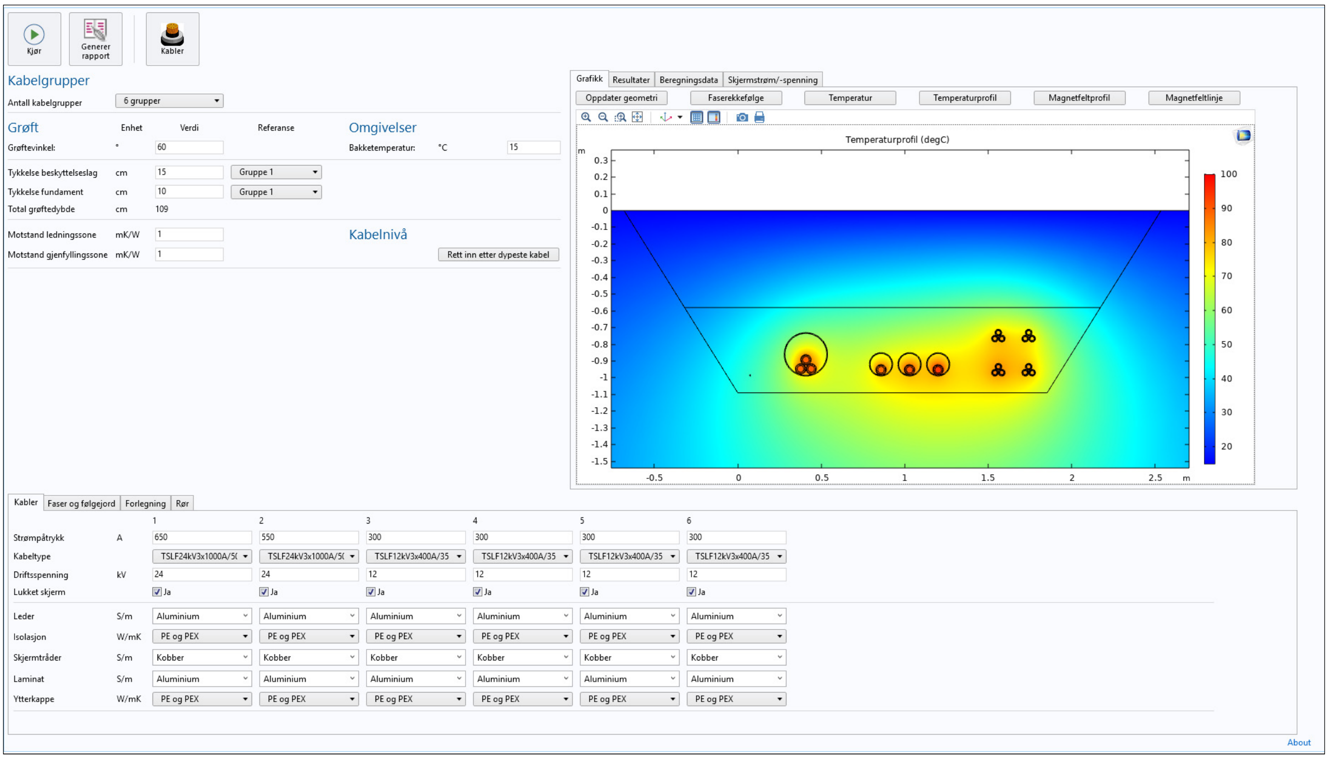


*Figure 3: Layout of the graphical user interface. The text in the GUI is in Norwegian.*

- For cables in pipes, comparison of FEA models to IEC 60287 gives a maximum deviation of 8% for the road crossing and 12% for the cable in an inclined pipe. Effects such as poor direct contact between cable and pipe surfaces, and longitudinal convection, are likely effects that give these deviations.

## ACKNOWLEDGMENTS

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