Close and Return

Determination of the transient temperature behaviour of submarine power cables and other transmission components using FEM analysis

STURM Sebastian, **PAULUS** Johannes**;** University of Applied Sciences Wuerzburg-Schweinfurt, (Germany),
BERGER Frank, Ilmenau University of Technology (Germany)
Sebastian.Sturm@fhws.de, Johannes.Paulus@fhws.de, frank.berger@tu-ilmenau.de

ABSTRACT

The paper describes the determination of transient temperature behaviour of an electrical system for power supply by measurements and how a Finite element Method (FEM) model was created and verified. With the verified simulation model any type of load cycles can be calculated. The approach is suitable for both AC and DC components. The procedure is applied to an AC submarine power cable for transmission of electrical power. Here, the load-dependent temperature behaviour is of particular interest. The current carrying capacity can be determined in dependence of the environmental conditions.

KEYWORDS

FEM Analysis; submarine power cable; transient temperature behaviour;

INTRODUCTION

In order to implement the connection of offshore wind turbines to an electrical grid there is on the one hand, the possibility of power transmission by alternating current and on the other hand the combined transmission with direct current. Particularly for very long transmission distances the partial DC variant is useful since the transmission range is limited with AC submarine power cables. An illustration of the transmission chain for partially DC transmission is shown in Fig. 1.

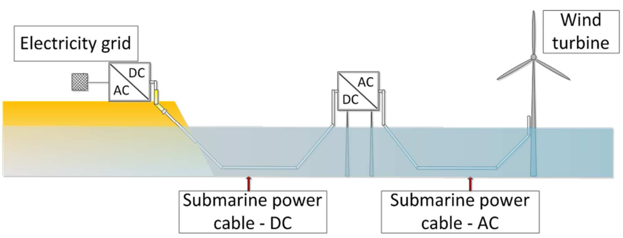

Fig. 1: Illustration of partial DC power transmission from offshore wind turbines to electricity grid

In the transmission chain, each component is subject to special requirements. Submarine power cables should not permanently exceed the maximum permissible temperature of insulating compound, otherwise the insulation material could be damaged and thus the submarine power cable is at risk of loss. To avoid a failure, a detailed knowledge about the thermal behaviour of the submarine power cable is necessary. Guides about the losses occurring in a submarine power cable can be found in the IEC 60287-1-1 [2] standard. For DC power cables the DC resistance of the conductor and the current are the relevant variables. For AC power cables the influence of skin and proximity effect, also eddy current, dielectric, and magnetic losses must be taken into account.

In order to come to know the thermal behaviour of a component, the material properties of the cable have to be known. In a stationary examination the thermal conductivity λ (W/mK) of the materials are crucial. In this paper, however, the transient temperature behaviour of a submarine power cable is analyzed. Therefore the density ρ (kg/m^3) and the specific heat capacity c_p (J/kgK) are important, too. A submarine power cable is a composite of different materials with varying thermal properties. Metallic components have a very high thermal conductivity. Non-metallic insulating materials such as polyethylene have very low conductivities. Heat capacity and density are also subjected to a wide range.

Temperature distributions in components for electrical power transmission have significant influence on the transmittable power. The already mentioned maximum tolerable temperature of the insulation material is important. Other interesting effects such as temperature-dependent electrical conductivity and thus the distribution of the electric field in DC applications are dependent of temperature as well. For AC applications, the electrical conductivity of the metallic components and thus the magnitude of eddy-current, resistive and dielectric losses are dependent on the temperature distribution.

The paper describes the determination of the transient temperature behaviour of an AC submarine power cable by measurements in a test rig and also the buildup of a FEM simulation model based on the measured data. Using the simulation model, each type of load change can be simulated. The approach is suitable for both AC and DC components. According to the occurring losses heat sources must be specified in the simulation model.

The load-dependent temperature behaviour is of particular interest. The knowledge of the time-dependent temperature distribution may allow an increase of the transmission power. Until the critical temperature is reached a higher power rate can be transported.

Test Rig and measurements

The test rig consists of a transformer, several power lines and the investigated submarine power cable. The transformer provides three-phase AC with a maximum current of 600 A at a voltage of 5 V. The transformer is connected to the submarine power cables and operates in short circuit. The submarine power cable has a length of 1.15 m. The temperature is detected at the conductor, on the cable surface and also the ambient temperature is measured. The power loss in the submarine power cable must be known for analysis as well. Therefore the voltage drop across the conductors of the submarine power cable and the current through the conductors are measured. In Fig. 2 the experimental setup is shown.

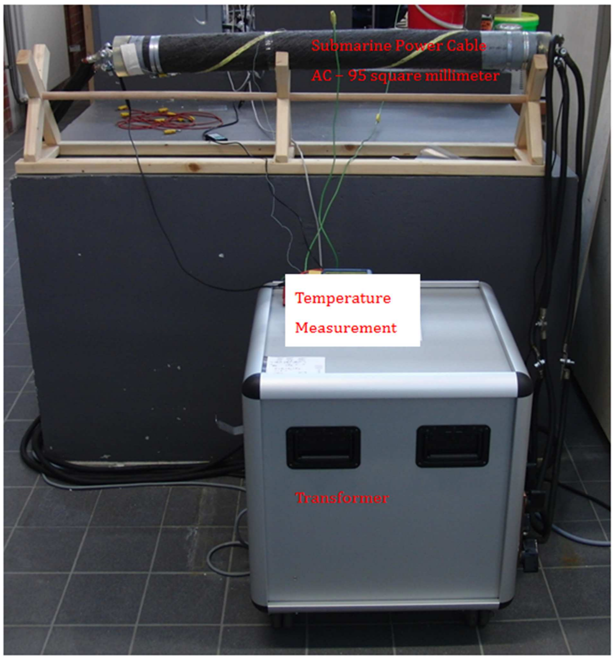

Fig. 2: Transformer to produce ohmic losses in a short piece of a submarine power cable

As an example a voltage drop of 0.1 V per conductor and a current of 300 A results in consideration of the measured power factor of 0.7 to a power loss in the entire cable of 63 W. With the total cable length of 1.15 m there is a power loss of 55 W/m. Fig. 3 shows the imprinted load profile on the submarine power cable.

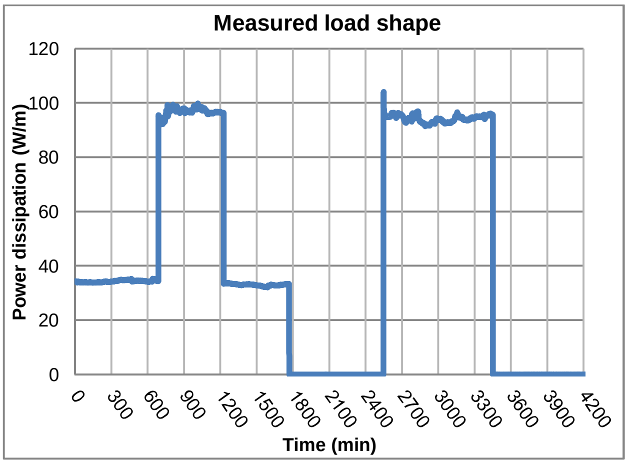

Fig. 3: Measured load shape imprinted to the submarine power cable

This load shape is used to verify the simulation model. The resulting temperatures at the submarine power cable are shown in Fig. 4.

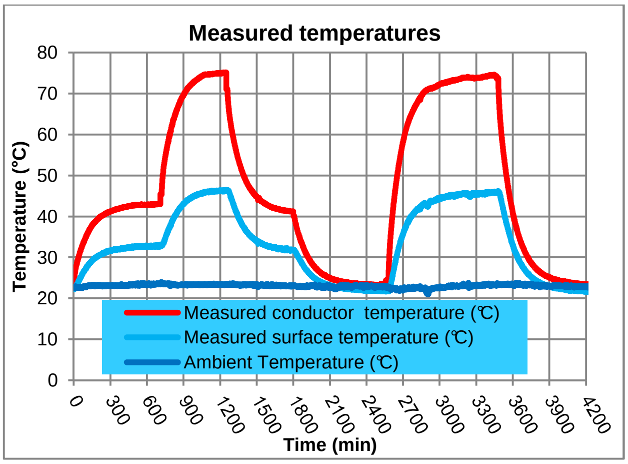

Fig. 4: Measured temperatures at conductor, cable surface and ambient temperature

The specified load profile can easily be understood by the measured temperatures. The temperature was recorded over a period of 70 hours. As it can be seen in the temperature profile, it takes time until the temperatures in the cable have stabilized to a stationary value. The measured temperatures are used to verify the simulation model.

FEM Simulation Model

The submarine power cable is modeled as a two-dimensional FEM simulation model. The simulation tool COMSOL Multiphysics can be used to simulate single and coupled phenomena with heat transport and electrodynamics. In the simulation model, the corresponding material properties in the domains must be specified, as well as the boundary conditions at the edges.

Setting the material conditions

The FEM model of the submarine power cables is built up as follows: Three copper conductors with the insulation materials, the steel reinforcement of the cable summarized to a cylinder and the yarn surrounding the cable. The polyethylene (PE) filler materials, air gaps and other remaining materials are combined. This "virtual" filler contains the summarized material properties of the individual materials. The material properties of this "virtual" filling material should be similar to the material properties of PE since it consists mainly of the combined material. It is important to eliminate the uncertainties by verification with measured values. Fig. 5 shows the simplified FEM simulation model of the submarine power cable as well as the meshed model.

Close and Return

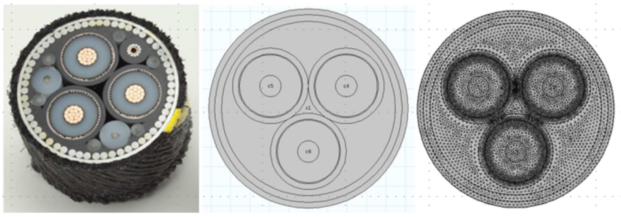

Fig. 5: Examined AC submarine power cable (left) and the simplified FEM Model (middle) and the meshed FEM Model (right)

In the following table the material conditions of the simulation model are listed.

Table 1: Material properties

Material	Thermal conductivity λ (W/mK)	Density ρ (kg/m³)	Specific heat capacity c_p (J/kgK)
Conductor (copper)	400	8700	385
Insulation (HD Polyethylene)	$0.45 - 0.012 \cdot \vartheta(°C)$	1000	2100
Shield (Copper/Steel)	40	7850	475
Armoring (Steel)	45	7850	475
Yarn (Synthetic fibers and bitumen)	0.3	400	600
Filling Material	$0.45 - 0.012 \cdot \vartheta(°C)$	1000	3000

By using the material data given in Table 1, the simulated and measured temperature profiles show a good correlation. All uncertainties became considered by adapting the filling material. The thermal conductivity of polyethylene is temperature dependent. The function is extrapolated from [1 page 93] for HD-PE. This function is also used for the filling material which consists mainly of polyethylene. The maximum permissible temperature for the used insulation compound XLPE is mentioned in [3] as 90 ℃. In the following analyses these temperatu re is used as the maximum allowable temperature.

Setting the boundary conditions

The measured power dissipation as shown in Fig 3 was assigned to the conductors. At the boundary of the simulation model heat transfer coefficients are given to take into account the convective heat flux and the heat emitted by radiation. The heat flux by radiation $\dot{q}_{rad}$ (W/m²) is according to [1].

$$\dot{q}_{rad} = \varepsilon \cdot \sigma \cdot \left(T^4 - T_{Amb}{}^4\right) \qquad [1]$$

ε = Emission coefficient 0.8 (-) [1]

σ = Stefan-Boltzmann-constant $5.67 \cdot 10^{-8}$ (W/m²K⁴)

T = Cable surface temperature (K)

T_{Amb} = Ambient temperature (K)

The emission coefficient is set in accordance with IEC 60287-1-1 to 0.8. The heat flux by convection $\dot{q}_{con}$ (W/m²) is taken into account by [2].

$$\dot{q}_{con} = \alpha_{con} \cdot (T - T_{Amb}) \qquad [2]$$

α_{con} = Heat transfere coefficient by convection (W/m²K)

T = Cable surface temperature (K)

T_{Amb} = Ambient temperature (K)

The heat transfer coefficient due to convection α_{conv} can be estimated with VDI Wärmeatlas [4]. The heat transfer coefficient depends on the temperature difference between cable surface and ambient temperature. Present air movement has a large influence on the heat flux by convection. A good agreement between measured and simulated results of surface temperature was reached by using a temperature-dependent heat transfer coefficient by convection according to Fig. 6.

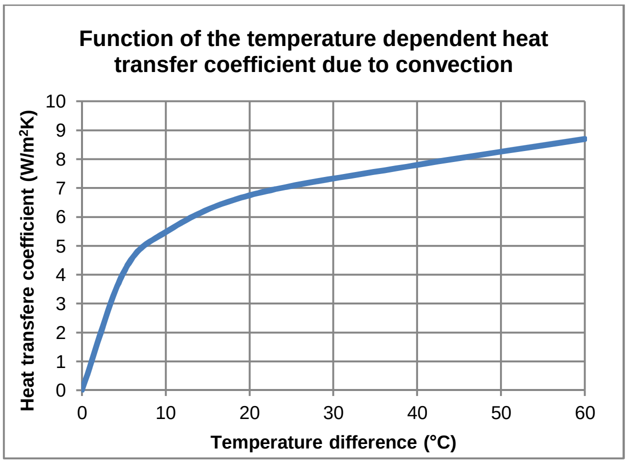

Fig. 6: Temperature dependent heat transfere coefficient to consider convective cooling

This heat transfer coefficient used as a boundary condition is higher than calculated in [4]. It is calculated just for natural convection and therefore in reality the measuring conditions ensure larger heat transport. Heat flux by radiation and convection appear in parallel so in the simulation these heat fluxes are added. The simulation result at a specific time is shown as an example in Fig. 7.

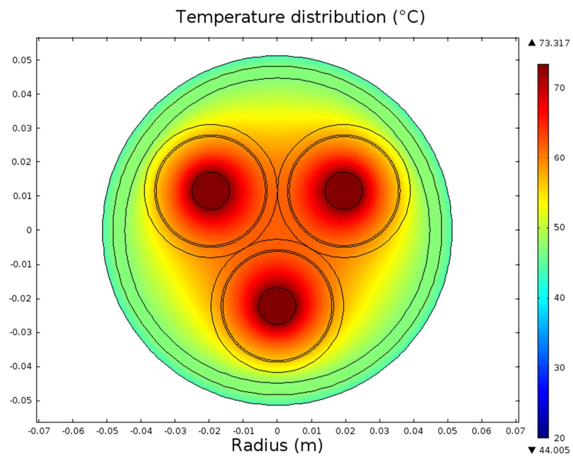

Fig. 7: Simulated temperature distribution in a submarine power cable

Based upon the color scale, the temperature distribution can be evaluated in the power cable. As expected the highest temperature appears at the conductors. The cable surface temperature is 44 ℃.

Comparison of simulated and measured temperatures

The simulated and measured temperatures of the conductor and cable surface are shown in Fig. 8.

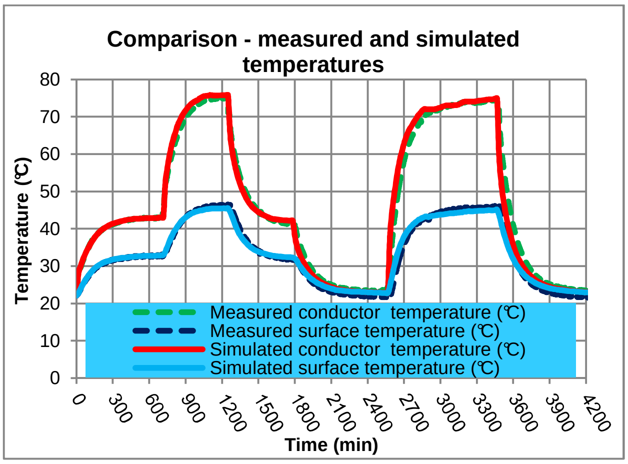

Fig. 8: Measured and simulated temperature profiles

In general the curves show good agreement. The stationary forming temperatures are nearly identical. The specified thermal conductivities in the model correspond to the conditions in reality. By using a specific heat capacity of 2100 J/kgK for the filling material, which would be similar to the existing materials, larger deviations of temperatures occur during the warm up and cool down. With the adjustment of the heat capacity of the filler to 3000 J/kgK the deviation is lower so the heat capacity of the submarine power cable is simulated more realistic. Geometric differences in simulated and real existing power cable are considered in this way. For instance the stranding of the conductors and PE fillers cause different heat capacities. In a 2D simulation model all parts are assumed as straight cylinders.

The simulation model is thus verified. Transient temperature fluctuations can be simulated.

Examination of the maximum admissible power dissipation for stationary and transient conditions

The current carrying capacity under stationary conditions can now be calculated easily. In Fig. 9 the head of the conductor temperature is plotted as a function of the power dissipation.

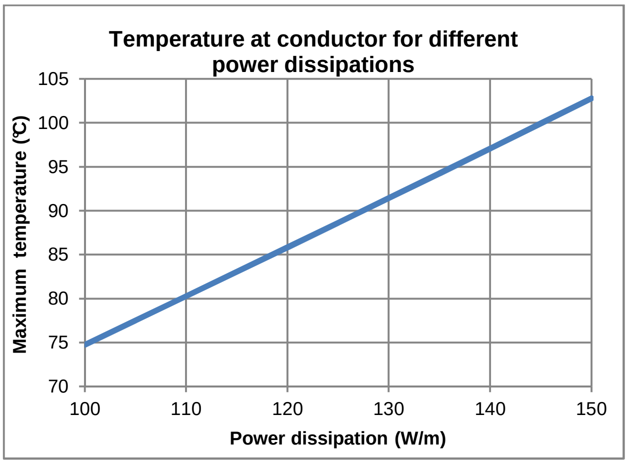

Fig. 9: Maximum cable temperature in dependence of power dissipation

A conductor temperature of 90 ℃ is reached at a pow er dissipation of about 128 W/m.

As already mentioned, the thermal inertia of the submarine power cable is tested too. Assuming, as in an offshore application entirely possible short-term power dissipation leaps with large power to be transmitted and in the meantime lower transmission power, it could be possible to transmit these performance boosts without reaching critical temperatures. In Fig. 10 some of the power dissipation profiles used for investigations are shown.

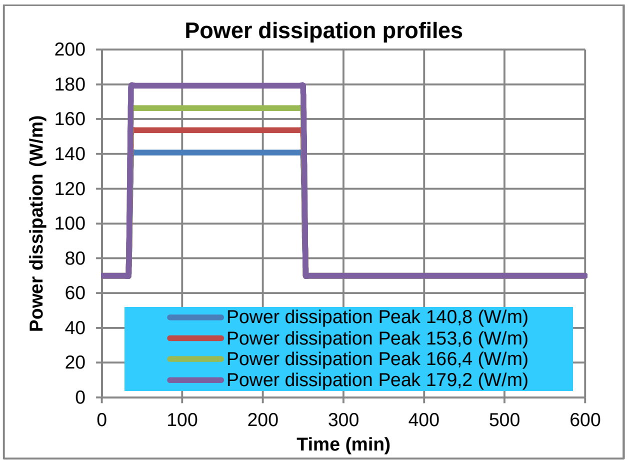

Fig. 10: Power dissipation profiles to analyze transient temperature behaviours

A power loss was imposed to the submarine power cable until the stationary state is reached according to a power dissipation of 70 W/m. Then the power dissipation is suddenly increased for a longer time. The power dissipation drops back after 210 minutes to the initial value of 70 W/m. Depending on the power dissipation, the maximum permissible conductor temperature was achieved faster or slower. Short-term overloads from 10 % to 40 % above the maximum tolerable power dissipation at different initial conditions were considered.

In Fig. 11 the temperature profiles for different cable load profiles are shown starting from a stationary power dissipation of 70 W/m.

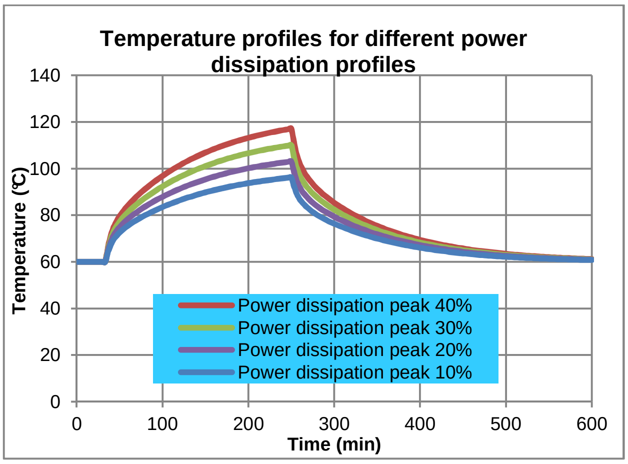

Fig. 11: Temperatur profiles for different load profiles

With a power dissipation of 140.8 W/m complying 10 % overload (Fig. 11) the maximum permissible cable temperature is reached after two hours (120 min). An overload of 40 % according to a power dissipation of 179.2 W/m the maximum temperature is reached after 43 min. In both cases the power overload started at a stationary conductor temperature of 60 ℃. Generall y, the time until the maximum temperature is reached can be derived from the model. This varies with the performance of initial conditions. The times obtained from the simulation are listed in Table 2.

Table 2 Time to reach 90 ℃ for different power dissipations and stationary start conditions

Stationary power dissipation (W/m)	Stationary cable temperature (℃)	Time to reach 90 ℃ with different power dissipation peaks (min)			
		140.8 (W/m) 10 %	153.6 (W/m) 20 %	166.4 (W/m) 30 %	179.2 (W/m) 40 %
50	49	**163**	**110**	**83**	**63**
70	60	**120**	**80**	**57**	**43**
100	74	**87**	**50**	**30**	**20**

The former conditions have a significant influence. Comparing previous stationary cable temperatures of 49 and 74 ℃ the maximum tolerable temperature is reac hed twice as fast for 10 % overload. For higher power dissipation peaks the critical temperature is reached up to three times faster. The degressive temperature rise caused by the rapid increase in power dissipation is reflected in the calculated times. A linear increase of power dissipation peak results in a nonlinear increase of time.

SUMMARY

Based on measurements on a test rig a FEM simulation model of a submarine power cable was verified. The verified simulation model allows determining the maximum permissible power loss in the power cables. For the arrangement (cable in air) a maximum power dissipation of 128 W/m is tolerable. Based on the transient observations the time to achieve the maximum cable temperature overload for different initial conditions was determined. The approach can be transferred for each cable AC as well as DC. Depending on previous conditions an overload of 10 to 20 % (140.8 and 153 W/m) is possible for 80 up to 163 minutes. (Provided a previous stationary power dissipation of 50 W/m or 70 W/m) Larger power overloads with higher previous temperatures are less interesting since the time until the critical temperatures are reached is not that long. Considering the previous temperature profile, longer overloads of power dissipation are possible with a suitable monitoring.

OUTLOOK

In this study an AC submarine power cables was analyzed. The power cables are located in the seabed up to three meters deep. The seabed has a thermal conductivity between 1.4 W/mK and 2 W/mK. These conductivities are typical values for North Sea and Baltic Sea. The thermal resistance of the seabed must be considered in order to determine the maximum conductor temperature in a real laid power cable. Although the seabed reduces the heat transfer from the cable surface, otherwise the large heat capacity of the seabed should allow a greater transient overload. For further investigations the thermal influence of the seabed must be recorded and evaluated. With the influence of the seabed and the verified cable model different load cycles can be examined in detail. Since the maximum admissible stationary power dissipation in reality is lower, transient views are even more interesting.

REFERENCES

[1] Hans Domininghaus, 1992, Die Kunststoffe und ihre Eigenschaften, VDI-Verlag, Düsseldorf

[2] IEC 60287-1-1, Edition 1.2 2001-11

[3] IEC 60502-2, Edition 2005-03

[4] Verein Deutscher Ingenieure, 2006, VDI Wärmeatlas, Springer, Berlin [u.a.]