Ampacity rating of directly buried distribution cables under the consideration of soil properties to improve efficiency of distribution networks

Constantin BALZER
TU Darmstadt - Germany
balzer@hst.tu-darmstadt.de

Christoph DREFKE
TU Darmstadt - Germany
drefke@geo.tu-darmstadt.de

Klaus HENTSCHEL
Bayernwerk AG - Germany
klaus.hentschel@bayernwerk.de

Volker Hinrichsen
TU Darmstadt - Germany
hinrichsen@hst.tu-darmstadt.de

Johannes STEGNER
TU Darmstadt - Germany
stegner@geo.tu-darmstadt.de

Jörg DIETRICH
HeidelbergCement AG – Germany
joerg.dietrich@heidelbergcement.com

Ingo SASS
TU Darmstadt - Germany
sass@geo.tu-darmstadt.de

ABSTRACT

The properties of the bedding material are of high importance for the ampacity rating of power cable systems. In order to specify the latter for directly buried cable systems, properties of the 39 main soil types in Bavaria/Germany have been studied. Results of the laboratory tests are presented with the help of three characteristic examples together with a short recall of the influence of soil characteristic on water movement. This is followed by an investigation of fluctuations of soil ambient temperature and suction potential throughout a year. It is found that for all kinds of soil, only yearly fluctuations in temperature are relevant. With regard to the suction potential, other effects such as precipitation and the presence of trees in the vicinity of the soil superimpose these yearly fluctuations, so that no general statements can be derived.

Finally, the possibility of the development of a bedding material is discussed that ensures optimal heat dissipation regardless of the environment.

INTRODUCTION

For years, the maximum voltage drop within a distribution grid has been the decisive criterion for dimensioning cable systems. However, by the appearance of dispersed reactive power injection, transformers with voltage regulation by tap changers and an increasing number of high power 110/20 kV transformer stations, voltage fluctuations (especially voltage rise due to photovoltaic) may more and more be controlled efficiently, shifting the focus back to the rated current limits imposed by thermal restrictions [1].

In order to prevent insulation faults in cable systems due to overheating, the related German standard DIN VDE 0276 sets, based on IEC 60-287, current limits regarding the thermal resistivity and the temperature of the soil, the number of cumulated cable systems as well as the load factor (which is defined as the relation of average load to maximum load within one load cycle) to which the cables are exposed. Nonetheless, the impact of the changes on load dynamics and the significant growth of peak load values due to dispersed power injection from photovoltaic-panels, particularly in Southern Bavaria, have not yet been considered sufficiently in detail.

Moreover, German distribution system operators (DSO) are subjected to an incentive regulation since 2007. Therefore, they have great interest to make the best use of the existing infrastructure, so that investment costs are kept at an optimal level regarding the intended quality of supply.

These three factors, namely:

- the growing importance of load restrictions due to thermal limits of the cables;
- the changed load dynamics that cables are facing;
- the incentive regulation that encourages DSO to optimize the investment in infrastructure quality expressed in terms of reliability (SAIDI, System Average Interruption Duration Index)

have led the German – especially the Bavarian – DSO to broadly review the cable ampacity ratings within their area of supply. As a result, an adopted rating system, taking into account the bedding conditions and the expected cable load, shall be defined. In consequence, this shall lead to a better use of the existing infrastructure and hence creating costs advantages through three mechanisms:

- Investment in network reinforcements that are necessary due to the steady increase of power injection of decentralized photovoltaics may be delayed without putting at risk the existing cable system.
- Investment in network reinforcements may be reduced by punctual reinforcement of the bedding material, using thermally optimized materials in order to mitigate hot-spots.
- Investment costs of network expansions may be reduced by using smaller cable conductor cross-sections in regions with favorable soil conditions.

INFLUENCES OF AMPACITY RATINGS OF DIRECTLY BURIED CABLES

The relevance of the characteristic of soil with regard to the ampacity rating of directly buried power cables has been pointed out by numerous publications. In [2], the impact of moisture migration under the influence of a thermal gradient (caused by heat injection from power cables) on the temperature development was illustrated using an implementation of the governing heat and mass transfer equations into a finite element model. Results underline once more the importance of initial moisture content and soil characteristics in order to determine the effect of load cycles on the temperature of power cables.

Nonetheless, [2] does not take into account the natural variations and influences on the soil moisture content and ambient soil temperatures. In [3], this was conducted in the framework of a long time examination, pointing out important factors such as the *"topography of routes, level of the water tables and possibility of evaporation due to the presence of trees, hedges grass etc."*. Unfortunately, quantitative conclusions have not been established. This is why the first stage of the current research project aims at two main objectives: Firstly, a broad overview of soil characteristics in Bavaria is established. Specific soils are investigated with the help of a laboratory test - developed at the TU Darmstadt department of Geothermal Science and Technology - that allows the simultaneous determination of thermal conductivity and water content of unsaturated soils as a function of soil water tension. Secondly, the main influences on natural temperature and moisture content fluctuations (e.g. impact of street surfaces) are named and examined regarding their relevance on further investigations.

DESCRIPTION OF WATER MOVEMENTS VIA POTENTIAL EQUATIONS

Analogically to electrodynamics or the heat conduction in solids, distribution and movements of water within a porous medium can be described with the help of a potential field. However, different sorts of potential may be distinguished. Most important are the geodetic potential Ψ_{z} that represents the impact of gravity, and the suction potential Ψ_{m}. The latter is a measure of the capacity of a soil matrix to retain water. It represents, therefore, the work that is needed for its extraction and is linked to adhesive forces at the grain surfaces and the capillarity of the soil matrix. In general, Ψ is measured in hecto-Pascal (hPa). Because the suction potential is opposed to the geodetic potential, the total potential can then be expressed as:

$$\Psi = \Psi_{\mathrm{z}} - \Psi_{\mathrm{m}} \qquad (1)$$

Just like the electric or thermic field, a difference in the total potential leads to a stream of water, whose value depends on the hydraulic conductivity. If the soil matrix is to be considered homogenous and of a constant hydraulic conductivity, the hydraulic flux can be specified using Darcy's law, when gravitation is defined to act in z-direction:

$$v = k \cdot \mathrm{grad}\, h = k \frac{\mathrm{d}h_{\mathrm{z}}}{\mathrm{d}z} - k \cdot \mathrm{grad}\, h \qquad (2)$$

With:

h: hydraulic head in m; $h = \frac{\Psi}{\varrho_{\mathrm{w}} \cdot \mathrm{g}}$
ϱ_{w}: density of water in $\frac{\mathrm{kg}}{\mathrm{m}^3}$
g: gravitational acceleration in $\frac{\mathrm{m}}{\mathrm{sec}^2}$
v: water flux density (Darcy velocity) in $\frac{\mathrm{m}}{\mathrm{sec}}$
k: hydraulic conductivity in $\frac{\mathrm{m}}{\mathrm{sec}}$

Furthermore, water must be conserved within the region of calculation, so that any divergence must result in a change of water content:

$$\mathrm{div}\, v = \varrho_{\mathrm{w}} \frac{\mathrm{d}\Theta}{\mathrm{d}t} \qquad (3)$$

With:

Θ: water content in $\frac{\mathrm{kg}}{\mathrm{m}^3}$

Finally, as it was already mentioned before, water content is directly linked to the suction potential, so that:

$$\Theta = \mathrm{f}(\Psi_{\mathrm{m}}) \qquad (4)$$

In the case that equation (4) could be described by a linear function, inserting equation (2) and (4) into (3) would lead to a Poisson-equation for the case of non-stationarity and to a simple Laplace-equation if there is no change in water content (i.e. a constant flux).

Non-linear behaviour of porous media

However, there are two obstacles of applying analytic solutions to the field problems mentioned above: Firstly, the hydraulic conductivity is not isotropic and strongly depends on the water content. Secondly, equation (4) is in general strongly non-linear. This is due to the fact that water is bound by adhesive forces at the surface of the grain, so that first of all, mineralogical components of the soil as well as the surface texture have an influence on the strength of water binding. Moreover, this strength decreases with increasing distance between the water molecules and grain surface, so that water within a large pore is extracted at lower suction tensions as water inside smaller pores. As a consequence, the relation between suction potential and water content gives significant indications about size and distribution of pores within the soil matrix.

Finally, equation (4) is not only strongly non-linear, it is also subjected to hysteresis effects, as air may be enclosed during irrigation and dewatering. The characteristic of this effect depends on tortuosity and geometry of the pores.

Water content is also important regarding the hydraulic conductivity, as low values lead to reductions in the effective cross section of water bridges. On the other side, the same mechanism that retains the water within the pores may hamper its conduction, so that soil with fine pores (such as clay) has a low but stable water conductivity, whereas soil with large pores (such as sand) has a good water conductivity at high saturation levels, but water conductivity decreases drastically, in the range of decades, with water content (and hence suction potential). In order to describe the two characteristics, van Genuchten as well as Mualem [4] developed corresponding approximations.

Nonetheless, some basic statements can be deduced from the presented equations. Firstly, regrouping equation (2) leads to the fact that the smaller the hydraulic conductivity, the higher the gradient of the hydraulic potential will be within the soil matrix if a specific water flux is given. This means that in the case of water evaporation on the soil surface, suction tension may be transported deeper into soils with a lower hydraulic conductivity (such as clay) as into such of higher hydraulic conductivity (like sand). Secondly, in case of good water retention, changes of suction potential will rapidly move through the soil matrix. This can be understood by replacing relation (4) with linear expressions of different negative slopes and then replacing and regrouping equation (3) with this term. The consequences of these two characteristics will be demonstrated with the help of a simplified example using the finite-element software "FEFLOW": A simplified model of a sand trench of 20 cm height and 40 cm width is placed 50 cm deep inside clay. Then, the soil is exposed to a step-sized increase of suction potential of 250 hPa at its surface in order to simulate an ongoing evaporation. The parameters of the Van Genuchten model for the associated water retention curves as well as those for the model from Mualem to describe the hydraulic conductivity are given in table (1).

Table 1: Parameter used to describe water retention and hydraulic conductivity

	Parameter	Unit	Sand	Clay
	pore volume	-	0.37	0.32
Unrestricted Van Genuchten	α	cm^{-1}	0.03	0
	n	-	50.00	1.01
	Ψ_r	$cm^3\ cm^{-3}$	0.016	0
	Ψ_s	$cm^3\ cm^{-3}$	0.363	0.334
	m	-	0.066	0.520
Mualem	τ	-	-1.602	-1.031

The suction potential as well as the water content are recorded at a depth of 80 cm inside the clay as well as at 60 cm inside the sand trench. Figure (1) shows the result.

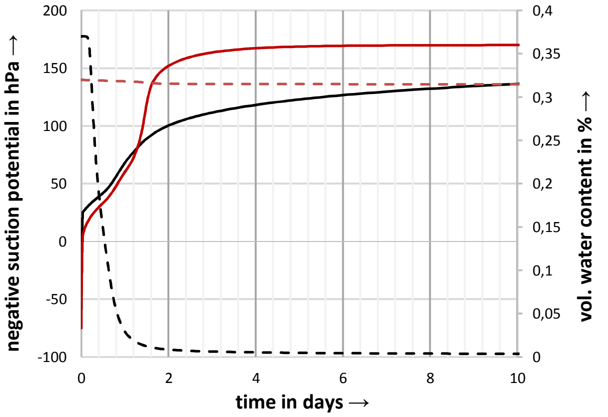

Figure 1: Suction potential (full line, primary axis) and water content (dotted line, secondary axis) at 60 cm depth in sand (black) and 80 cm depth in clay (red) as a function of time

As expected, the suction potential inside the clay changes within only a few days, whereas the potential inside the sand trench aligns with a much longer time constant.
Nonetheless, the change in suction potential has little impact on the water content of the clay, whereas the sand dries rapidly within only a few days.
This example illustrates drastically that in order to establish ampacity ratings of cable systems on the conservative side, interactions with the surrounding soil must be taken into account.

SOIL PROPERTIES

The method of choice for measuring thermal conductivity, water retention characteristics and hydraulic conductivity simultaneously is an evaporation test. In addition to the standard design, the system is combined with a full-space line source to determine thermal conductivity [5].

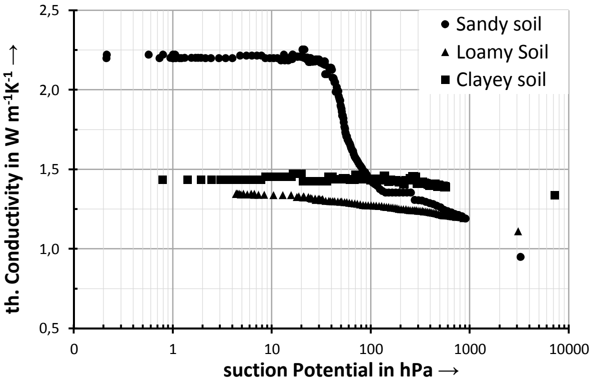

Figure 2: Thermal conductivity of some different soil samples as a function of capillary tension

In figure (2), the results for three different natural soil samples are shown, which exemplarily represent 39 different probes taken in different regions in Bavaria. The sandy soil is a fine to medium grained river sand, extracted west of the city of Aschaffenburg, the clayey soil a young valley deposit from the region of Gemünden/Main and the loamy soil is a diluvial deposit, taken east of Karlstadt/Main. The distribution of water within the pore system as well as the bonding force of this water influence the change in thermal conductivity with suction potential.

ENVIRONMENTAL IMPACTS

In a first attempt, variations and influences of ambient soil temperature as well as ambient soil moisture content shall be identified and assessed.

Variation in ambient soil temperature

From a theoretic point of view, the problem of determining the development of ambient soil temperature at a specific depth can be described as a one-dimensional heat transfer problem with periodic boundary stimulation. The configuration is displayed in figure (3), soil surface is placed at $y = 0$. If, in a first approximation, soil is to be considered as a solid with homogenous and linear heat conductivity, the equation to solve for $y < 0$ reduces to:

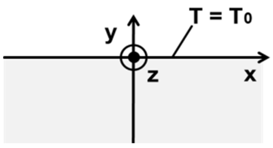

Figure 3: Set-up of a one dimensional heat transfer problem with a periodic boundary condition at y = 0.

$$\Delta T(y,t) = \frac{\partial T(y,t)^2}{\partial y^2} = \frac{1}{\kappa}\frac{\mathrm{d}T(y,t)}{\mathrm{d}t} \qquad (5)$$

Where κ denotes the thermal diffusity of the soil with:

$$\kappa = \frac{\lambda}{\varrho c} \qquad (6)$$

With:

λ: thermal conductivity in $\frac{\mathrm{W}}{\mathrm{m\cdot K}}$

c: specific thermal capacity in $\frac{\mathrm{kJ}}{\mathrm{kg\cdot K}}$

ϱ: mass density in $\frac{\mathrm{kg}}{\mathrm{m}^3}$

When describing the temperature oscillation at the surface as the real part of a complex phasor:

$$T_0 \cdot \cos(\omega t) = \Re\{\underline{T_0}\} = \Re\{T_0 \cdot \mathrm{e}^{\mathrm{j}\omega t}\} \qquad (7)$$

Equation (5) simplifies to:

$$\frac{\partial^2}{\partial y^2}\{\underline{T}(y,t)\} = \frac{j\omega}{\kappa} \cdot \underline{T}(y,t) = \underline{\mathrm{p}}^2 \underline{T}(y,t) \qquad (8)$$

With $\underline{\mathrm{p}}^2 = \frac{j\omega}{\kappa}$; $\underline{\mathrm{p}} = (1+\mathrm{j})\sqrt{\frac{\omega}{2\kappa}} = (1+\mathrm{j})\mathscr{k}$.

The solution of equation (8) can be derived as:

$$\underline{T}(y,t) = \underline{A}e^{\mathscr{k}y}e^{j\mathscr{k}y} + \underline{B}e^{-\mathscr{k}y}e^{-j\mathscr{k}y} \qquad (9)$$

Inserting the boundary conditions then yields $\underline{B} = 0$ and $\underline{A} = \underline{T_0}$, so that the temperature distribution inside the soil can, after building the real part of the solution according to equation (7), finally be described as:

$$T(y,t) = T_0 e^{\mathscr{k}y} cos(\mathscr{k}y + \omega t) \qquad (10)$$

In order to verify whether this well-known result [6] is still valid under the influence of percolation, temperature sensors at different depths have been placed inside the sandy soil of a cable test field, installed at TU Darmstadt [7]. The result for a depth of 0.7 m is shown in figure (4), the dashed line representing the fundamental component.

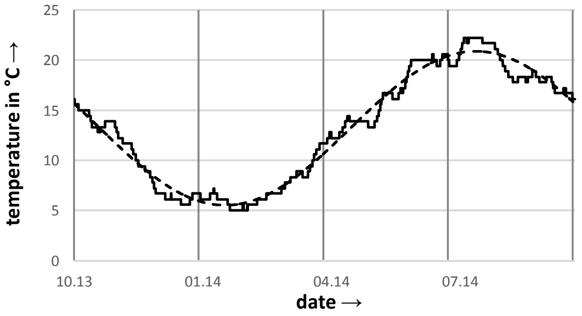

Figure 4: Measured development of ambient soil temperature at a depth of 0.7 m in a sandy soil at the cable test field of TU Darmstadt throughout one year

As it can be seen, there are no significant discrepancies between the measured signal and its fundamental component, so that, with regard to the precision needed, the simplifications under which equation (10) was established may be considered as justifiable.

This allows a simple examination of the amplitude of ambient soil temperature deviations throughout one year at cable laying depth as long as the average soil diffusivity is known. Therefore, the damping factor in equation (10) simply needs to be evaluated regarding different frequencies at a specific depth. In figure (5), this was performed for an exemplary soil with a diffusivity of:

$$\kappa = \frac{1}{3} \cdot 10^{-6}\,\frac{\mathrm{m}^2}{\mathrm{sec}} \qquad (11)$$

In addition, the damping factors regarding the measured diffusivities of the extracted soil probes are marked for daily, weekly, monthly and yearly oscillations.

Quintessence of figure (5) is that for the examined soil and depth, yearly variations are damped to about 70 percent of their amplitude at the soil surface. In contrast to this, daily to monthly variations have virtually no influence on the soil ambient temperature. Other influences such as water percolation can be neglected. This result is in line with older references [8].

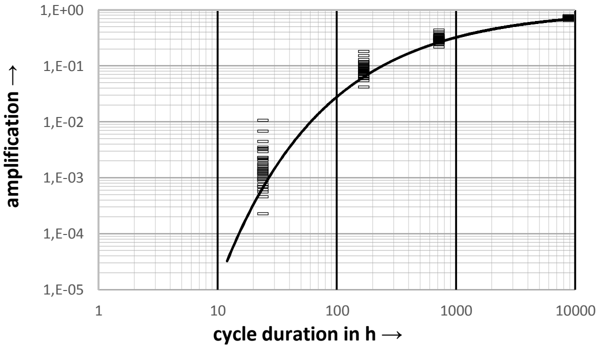

Figure 5: Amplification of the boundary temperature oscillation at y = -0.7m for a soil of a thermal diffusivity in (7) with respect to the cycle duration. One year corresponds to 8760 h

However, the influence of the ambient soil temperature is already quantified in the relevant standards. Under the aspect of altered cable loads, this finding shows no direct benefit to an enhancement of cable ampacity ratings, because high peaks caused by power injection from photovoltaic panels mainly occur in the summer months. However, the impact of lower ambient soil temperatures regarding the moisture movement under the influence of the thermal gradient must still be examined.

Variation in ambient soil water content

Regarding the variation in ambient suction potential, it is difficult to express tangible statements as it was done in the section above. In general, a yearly variation with peaks of suction potential (i.e. water saturation) during winter is pointed out in [6]. However, harsh changes of suction potential in the course of precipitation and strong non-linearites in both, the unsaturated water conductivity as well as the water content as a function of suction potential, lead to strong discrepancies to a yearly oscillation. This is confirmed by local measurements on the cable test field, where, amongst others, two tensiometers have been placed at a depth of 50 cm in silt as well as sand.

Apart from the soil conditions, there are numerous local influences on the suction potential distribution and their changes in time: First of all, the distance to phreatic water affects the geodetic potential. Then, water and vapour transportation through evaporation depends largely on the surface of the soil and weather conditions, despite the fact that, in soil matrixes with high porosity, the capillary contact between layers next to the surface and deeper ones can cut off, leading to an end of water flux. Furthermore, roots of trees can lead to a significant change of the suction potential distribution up to 10 m away from the trunk, as it was shown in [9]. It is clear that with regard to the number of influences, their impact needs to be investigated further, using a finite-element modelling, based on the collected soil parameters.

DEVELOPMENT OF FLUIDIZED BACKFILL-MATERIALS

As it was shown in the sections above, water content and water retention capability of an unconsolidated backfill-material is of greater influence in a partial-saturated environment. Therefore, one approach to create a backfilling material with enhanced thermal and hydraulic performance is the reduction of the porosity by optimizing the grain size distribution.

Once this has been achieved, adding some heat conducting additives leads to further boosting of heat conductivity.

Such a recipe was developed in cooperation with a German building material company and tested with the help already mentioned laboratory facilities. The result is shown in figure (6).

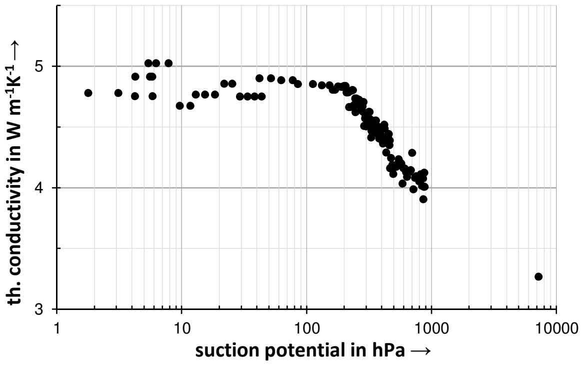

Figure 6: Thermal conductivity of a specially developed backfilling material as a function of the suction potential

It can be seen that for a suction potential of up to 1000 hPa, heat conductivities of more than 4 $Wm^{-1}K^{-1}$ are achieved. Furthermore, the final product shows clearly improved volume stability.

The option of adding rather costly heat conducting additives must always be considered under the premises of the application. In order to ease the effect of single hot spots such as the crossing of other heat-dissipating sources within urban areas, highly conducting materials may the most effective solution.

CONCLUSION AND OUTLOOK

As it was discussed in detail, there are plausible arguments to review cable ampacity ratings. In order to do so, a large data basis of the 39 main soil configurations in Bavaria was established, including important relations of water content and heat conductivity as a function of water suction potential. Before examining the processes under the influence of heat injection from cables, first the environmental impacts on soil temperature and moisture content have been studied. The main conclusions are:

- Interactions of bedding materials with the natural environment via capillary contact can lead to reductions of water content of the bedding. This may lead to higher thermal resistances, i.e. lower ampacity ratings.
- With respect to temperature oscillations, only seasonal variations must be taken into account, whereas percolation has no significant influence. Moreover, the soil type has little impact on the natural temperature oscillation.
- The enhancement of load capability due to lower soil temperatures is already included in the present standards in a traceable way. However, as high peaks due to power injection from solar panels occur in summer, there is no useable benefit from lower soil temperatures in winter.

Nevertheless, the distribution of suction potential and the impact of various factors, such as evaporation characteristics and vegetation, must be further investigated.

Once these effects have been quantified, a modelling of the combined heat and mass transportation mechanisms under the influence of natural percolation is foreseen, allowing a precise determination of the ampacity ratings of cable systems. This shall lead to cost-efficient investment policies.

MISCELLANEOUS

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