Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 94 (2016) 399 – 408

Energy Procedia

13th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2016, 20-22 January 2016, Trondheim, Norway

Optimal Operation Voltage for Maximal Power Transfer Capability on Very Long HVAC Cables

Til Kristian Vrana*, Olve Mo

Sintef Energi, Trondheim, Norway

Abstract

An analytical approach towards the operation of very long HVAC cables has been developed. The main physical phenomena have been expressed with simplified analytical equations. A comparison with numerical simulations has shown acceptable accuracy. A set of long distance cable parameters has been introduced. The main conclusion is that beyond a certain specific cable length, the operation voltage should be optimised rather than set to the rated voltage value. Operation at the power factor $\cos(\phi_P) = 1/\sqrt{2}$ has been found to be optimal with regards and power transmission capability.

The developed equations can help to gain a better understanding of the subject matter, and the introduced long distance parameters enable to easily compare the long distance capabilities of different cables. It is concluded, that for very long HVAC cable projects, it makes sense to consider cables with very high voltage rating, even though they might not be operated at rated voltage. Such cables can be beneficial due to their thicker insulation layer resulting in lower capacitance. The results also highlight the importance of HVAC cables with low capacitance for very long distance applications, which might lead to a new niche market of specialised cables.

Peer-review under responsibility of SINTEF Energi AS

Keywords: Long distance transmission; HVAC; offshore wind power

1. Introduction

Some offshore wind power plants are located far away from shore. These remote locations require long export cables and both HVAC and HVDC transmission solutions can be applied. There is a generally accepted principle of the economic break-even-length for HVAC and HVDC transmission, meaning the transmission distance where AC and DC solutions would have the same total cost. For any transmission length beyond the economic break-even-length, HVDC is advantageous, while for shorter lengths HVAC is advantageous.

* Corresponding author Tel.: +47-45676594
E-mail address: vrana@sintef.no

1876-6102
Peer-review under responsibility of SINTEF Energi AS
doi:10.1016/j.egypro.2016.09.202

Even though the concept of the economic break-even-length is generally accepted, there is no generally accepted quantification, as the exact length depends on many factors of the specific case. However, regarding cable applications, the break-even-length is often referred to as being in the range 50 − 100 km. This has caused a lack of interest for seriously considering HVAC transmission schemes for very long distances.

Many wind power plants in the German Bight are pioneer projects when it comes to remoteness. Based on the economic break-even-length concept, HVDC-based long distance power transmission for grid connection has been chosen for all remote offshore wind power plants in that area. However, experience has shown, that these offshore HVDC links can be more costly than expected [1], indicating that the economic break-even-length has been underestimated.

Very long HVAC cables have therefore recently become a hot topic, especially for grid connection of remote offshore wind power plants. It is important to quantify for how long transmission distances HVAC cable systems can be applied. The world's longest HVAC cable is the 163 km cable to the Martin Linge oil&gas platform which is under construction at the time of writing [2].

1.1. Background

For the same conductor cross section, the transmission capacity of HVDC cables are larger than for HVAC. This is clearly seen in Fig.1 taken from [3]. The figure shows the maximum transfer capacity of cables of different voltage rating, operated at rated voltage with reactive compensation only at one end.

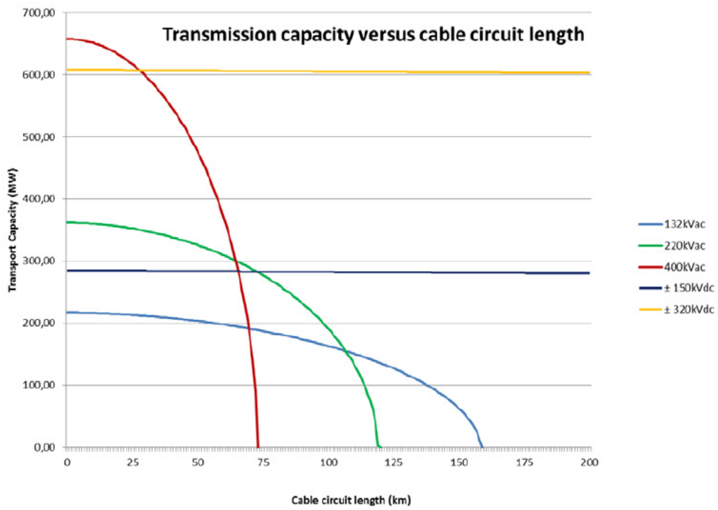


Fig. 1: Transmission capacity versus length of the cable system, 50 Hz, 1200 mm^2 Cu (taken from [3])

These maximum transfer capacities presented in Fig.1 are calculated based on the assumptions that the cable is operated at its rated voltage. For HVAC cables of 'normal' length, the transmission capability increases with increasing voltage. However, for very long HVAC cables this is not true, as it will be shown in this article.

1.2. Scope

This article explores to what extent one may optimise the operating voltage of a given cable to increase the transmission capability of very long cables. The scope of this article is limited to explore to what extent the technical transmission capabilities can be increased by optimising the operation voltage. It remains, however, beyond the scope of this article, to investigate to what extent this can contribute to a cost reduction for remote offshore wind power projects.

2. Approach

Very long HVAC cables is a subject which has not been extensively addressed before, mostly due to a lack of relevance for real application. No existing theory on the subject was found by the authors, creating the motivation to develop that missing theory. For achieving this goal, a purely analytical approach was chosen. The focus was on deriving the basic equations, and understanding the main phenomena. The goal was to identify the relationships between cable length, cable parameters, operation voltage, power transmission capability and efficiency.

To be able to derive simple analytical equations, it was necessary to heavily simplify the approach. A lumped parameter model consisting of resistive losses and cable capacitance has been used. Such a strongly simplified approach can of course only serve as a starting point for more accurate calculations. However, as the focus here was set on describing the most relevant physical phenomena with easy-to-handle equations instead of grasping all the details, the simplifications and the hereby introduced error was accepted. The main simplifications are:

- **Inductance:** Attempts have failed to find equations considering inductance, that are suitable for taking the derivative and that lead to simple comprehensive expressions for all the derivations done here. It was therefore necessary to ignore cable inductance.
- **Resistive Voltage Drop:** The voltage difference between sending and receiving end is disregarded. A consequence of this is that symmetric compensation can easily be applied. Considering the voltage drop would require asymmetric compensation for optimal utilisation of the cable.
- **Voltage Profile:** The voltage profile on the cable has been ignored. The voltage in the midpoint of a HVAC cable is higher than at its ends, and this effect is disregarded for all the calculations here. Operating the cable ends at maximal voltage would result in a voltage limit violation at the midpoint. It has therefore been considered that the operating voltage cannot exceed the rated voltage, to leave a margin for the raised midpoint voltage. Ignoring the raised midpoint voltage also results in an slight underestimation of the reactive charging current.
- **Reactive Compensation:** 50 % reactive compensation is assumed on each end of the cable. The losses of reactive compensation equipment have not been considered here. The calculated efficiencies therefore only consider the cable itself.

For visualising the results, it is necessary to quantify the cable parameters. For the cause of visualisation, an example cable has been selected, and the cable parameters of this example cable are used for calculating the long distance transmission parameters of that cable. These are used for plotting the figures.

The chosen example cable is a three-core cable with $A = 1000\ \text{mm}^2$ copper conductors. The insulation material is Cross-Linked Poly-Ethylene (XLPE), and the cable has an armour. The cable data, taken from manufacturer brochures [4] [5] [6] [7], is given in Table 1.

Table 1: Parameters of the example cable

Parameter	Value	Unit
C'	0.18	µF / km
R'	0.0275	Ω / km
$I_{\max}$	0.825	kA
$U_{\max}$	275	kV
ω	100π	1 / s
L'	0.39	mH / km

The maximum allowed voltage for the given cable is actually 300 kV, but for the calculations here, the nominal voltage of 275 kV has been used as an upper limit for the operating voltage, to leave a margin for voltage variations throughout the cable (which have not been considered in the calculations). The inductance parameter given is only used for the validation, but it is not part of the simplified equations.

3. Simplified Analytical Description of the Electrical Cable Properties

In this article, the rated voltage is called U_{max}, as this value is here used as the highest admissible operation voltage (not to be confused with temporary voltage limits, which are much higher than rated voltage). In the following calculations the index ' $*$ ' is used to write variables with their value in relation to the given maximum value:

$$I_* = \frac{I}{I_{\mathrm{max}}} \qquad U_* = \frac{U}{U_{\mathrm{max}}} \qquad l_* = \frac{l}{l_{\mathrm{max}}} \tag{1}$$

3.1. Parameters

The maximal power which a cable can transmit appears at maximal voltage and maximal current, when the cable is very short ($l \approx 0$) so that the charging current is neglectable ($I_{\mathrm{q}} \approx 0$), leading to ($I_{\mathrm{d}} \approx I_{\mathrm{max}}$).

$$P_{\mathrm{max}} = \sqrt{3} U_{\mathrm{max}} I_{\mathrm{max}} \approx 393 \text{ MW} \qquad \text{(for the example cable)} \tag{2}$$

With the simplifications applied here, the reactive current at each end of a HVAC cable is a function of the cable length and the operation voltage, following the equation : $I_{\mathrm{q}}(U, l) = \frac{\omega C' l}{2} \frac{U}{\sqrt{3}}$. Based on this, the maximal applicable cable length at rated voltage can be calculated, which is the length when the maximal current is equal to the reactive charging current $I_{\mathrm{q}} = I_{\mathrm{max}}$:

$$l_{\mathrm{max}} = \frac{\sqrt{12} I_{\mathrm{max}}}{\omega C' U_{\mathrm{max}}} \approx 184 \text{ km} \qquad \text{(for the example cable)} \tag{3}$$

The theoretical maximal losses in a cable appear at full current $I = I_{\mathrm{max}}$, maximal length $l = l_{\mathrm{max}}$ and a very low operation voltage $U \approx 0$, so that the charging currents can be neglected $I_{\mathrm{q}} \approx 0$ leading to all current being active current $I_{\mathrm{d}} \approx I_{\mathrm{max}}$. In this case the losses are: $P_{\mathrm{maxloss}} = 3R' l_{\mathrm{max}} I_{\mathrm{max}}^2$. Using Equation 2 and Equation 3, this can be rewritten as: $P_{\mathrm{maxloss}} = \frac{1}{2} \omega R' C' l_{\mathrm{max}}^2 P_{\mathrm{max}}$, leading to a constant, which links the maximal power to the maximal losses:

$$K_{\mathrm{loss}} = \frac{P_{\mathrm{maxloss}}}{P_{\mathrm{max}}} = \frac{1}{2} \omega R' C' l_{\mathrm{max}}^2 \approx 2.63\ \% \qquad \text{(for the example cable)} \tag{4}$$

3.2. Active and Reactive Current Expressions

Using Equation 3 and Equation 1, the reactive charging current can be expressed in an alternative way:

$$I_{\mathrm{q}}(U, l) = I_{\mathrm{max}} U_* l_* \tag{5}$$

Inserting Equation 5 into $I^2 = I_{\mathrm{d}}^2 + I_{\mathrm{q}}^2$, and solving this for I_{d} gives:

$$I_{\mathrm{d}}(U, I, l) = I_{\mathrm{max}} \sqrt{I_*^2 - U_*^2 l_*^2} \tag{6}$$

3.3. General Power Equations

The power infeed into a cable $P(U, I_{\mathrm{d}}) = \sqrt{3} U I_{\mathrm{d}}$ can be rewritten by using Equation 6 and Equation 2:

$$P_{\mathrm{feed}}(U, I, l) = P_{\mathrm{max}} U_* \sqrt{I_*^2 - U_*^2 l_*^2} \tag{7}$$

The resistive power losses on a cable are: $P_{\mathrm{loss}}(I, l) = 3R' \int_0^l I^2(\lambda) d\lambda$. The current can be split into its components ($I^2 = I_{\mathrm{d}}^2 + I_{\mathrm{q}}^2$). With the simplifications applied here, the active current component is constant throughout the cable length. The reactive charging current can be considered to have a linear profile from cable end $\left(I_{\mathrm{q}}(\lambda = 0) = I_{\mathrm{q}}(\lambda = l) = I_{\mathrm{q}}\right)$ to midpoint $\left(I_{\mathrm{q}}(\lambda = l/2) = 0\right)$. With these considerations, the integral can be solved:

$P_{\text{loss}}(I_{\text{d}}, I_{\text{q}}, l) = 3R'lI_{\text{d}}^2 + R'lI_{\text{q}}^2$. This can be rewritten as: $P_{\text{loss}}(I, I_{\text{q}}, l) = 3R'lI^2 - 2R'lI_{\text{q}}^2$. Using Equation 5, Equation 1 and Equation 4, this can be formulated as:

$$P_{\text{loss}}(U, I, l) = P_{\max} K_{\text{loss}} \left(I_*^2 l_* - \frac{2}{3} U_*^2 l_*^3 \right) \tag{8}$$

Based on Equation 7 and Equation 8, the power transfer (power at the receiving end) can be formulated:

$$P_{\text{trans}}(U, I, l) = P_{\text{infeed}} - P_{\text{loss}} = P_{\max} \left(U_* \sqrt{I_*^2 - U_*^2 l_*^2} - K_{\text{loss}} \left(I_*^2 l_* - \frac{2}{3} U_*^2 l_*^3 \right) \right) \tag{9}$$

Based on Equation 7 and Equation 8, also the efficiency can be formulated:

$$\eta(U, I, l) = 1 - \frac{P_{\text{loss}}}{P_{\text{infeed}}} = 1 - K_{\text{loss}} \frac{I_*^2 l_* - \frac{2}{3} U_*^2 l_*^3}{U_* \sqrt{I_*^2 - U_*^2 l_*^2}} \tag{10}$$

3.4. Specific Power Equations for Maximum Current at Rated Voltage

The maximum power flow through a cable appears logically at the maximum current flow $I = I_{\max}$. The voltage is fixed at its rated value $U = U_{\max}$. Removing current and voltage as variables simplifies the power equations.

$$P_{\text{feed}}(U_{\max}, I_{\max}, l) = P_{\max} \sqrt{1 - l_*^2} \tag{11}$$

$$P_{\text{loss}}(U_{\max}, I_{\max}, l) = P_{\max} K_{\text{loss}} \left(l_* - \frac{2}{3} l_*^3 \right) \tag{12}$$

$$P_{\text{trans}}(U_{\max}, I_{\max}, l) = P_{\max} \left(\sqrt{1 - l_*^2} - K_{\text{loss}} \left(l_* - \frac{2}{3} l_*^3 \right) \right) \tag{13}$$

$$\eta(U_{\max}, I_{\max}, l) = 1 - K_{\text{loss}} \frac{l_* - \frac{2}{3} l_*^3}{\sqrt{1 - l_*^2}} \tag{14}$$

4. Power Capability Optimisation

The maximum power flow through a cable appears logically at the maximum current flow $I = I_{\max}$. The current is therefore not considered as a variable but set to its maximal value.To find the optimal operation voltage for maximal power capability, it is necessary to take the derivative of Equation 7 with respect to the voltage: $\frac{dP(U,l)}{dU} = P_{\max} \frac{1}{U_{\max}} \sqrt{I_*^2 - U_*^2 l_*^2} + P_{\max} U_* \frac{1}{2} \frac{-l_*^2 2U_*/U_{\max}}{\sqrt{I_*^2 - U_*^2 l_*^2}} = \sqrt{3} I_{\max} \frac{1 - 2l_*^2 U_*^2}{\sqrt{1 - l_*^2 U_*^2}}$. This derivative is then set to zero $\frac{dP_{\text{opt}}(U_P,l)}{dU_P} = 0$, leading to: $2 \frac{l^2}{l_{\max}^2} \frac{U_P^2}{U_{\max}^2} = 1$. This expression can be solved to find the power-optimal operation voltage:

$$U_P(l) = \frac{U_{\max}}{\sqrt{2}} \frac{1}{l_*} \tag{15}$$

Based on Equation 15, the minimum length where operation at optimal voltage is applicable can be calculated. This is the length, where the optimal voltage is equal to the rated voltage $U_P(l_P) = U_{\max}$.

$$l_P = \frac{l_{\max}}{\sqrt{2}} \approx 130\ \text{km} \qquad \text{(for the example cable)} \tag{16}$$

Equation 15 can be inserted into Equation 5, leading to: $I_{\text{q}} = I_{\max}/\sqrt{2}$. Considering $I^2 = I_{\text{d}}^2 + I_{\text{q}}^2$ results in $I_{\text{d}} = I_{\text{q}}$. This shows that the optimal power factor for maximum power operation is:

$$\cos(\phi_P) = \frac{1}{\sqrt{2}} \approx 0,7 \tag{17}$$

4.1. Specific Power Equations for Maximum Current at Optimal Voltage

The maximum power flow through a cable appears logically at the maximum current flow $I = I_{\max}$. The voltage variable is replaced by $U_P(l)$. Removing current and voltage as variables simplifies the power equations.

$$P_{\text{feed}}(U_P, I_{\max}, l) = \frac{P_{\max}}{2l_*} \tag{18}$$

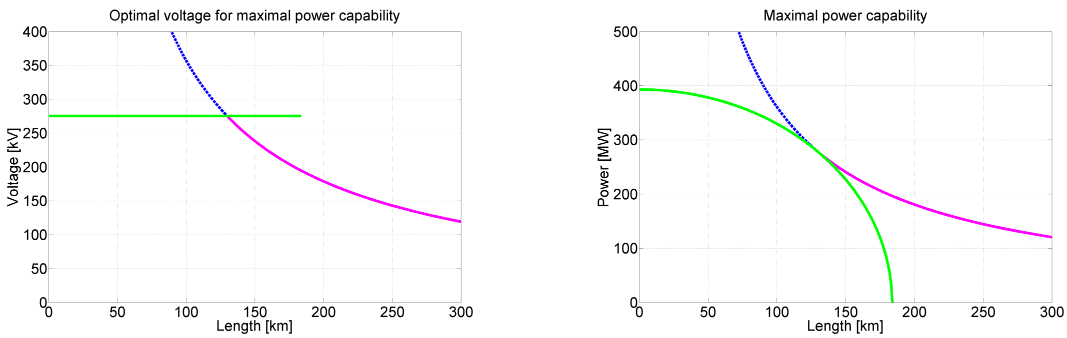
$$P_{\text{loss}}(U_P, I_{\max}, l) = \frac{2}{3}P_{\max}K_{\text{loss}}l_* \tag{19}$$

$$P_{\text{trans}}(U_P, I_{\max}, l) = P_{\max}\left(\frac{1}{2l_*} - \frac{2}{3}K_{\text{loss}}l_*\right) \tag{20}$$

$$\eta(U_P, I_{\max}, l) = 1 - K_{\text{loss}}\frac{4}{3}l_*^2 \tag{21}$$

4.2. Graphical Visualisation of the Equations

Fig. 2 shows a comparison of operation at rated voltage and operation at power-optimal voltage. Operation at rated voltage is displayed by a green curve. Operation at power-optimal voltage is displayed by a blue/magenta curve, where the blue section represents theoretical operation ($U > U_{\max}$, $l < l_P$) and the magenta section represents feasible operation ($U < U_{\max}$, $l > l_P$). The parameters l_P and $l_{\max}$ can clearly be observed in both figures. Fig. 2a displays Equation 15. Fig. 2b displays Equation 11 Equation 18. The green curve for operation at rated voltage with the cable parameters for the example cable is well in line with Fig. 1. The main difference is the doubled transmission distance capability due to the difference in reactive compensation at both ends (used here) and only at one end at Fig. 1.



(a) Operation at rated voltage and optimal voltage ($U = U_{\max}$ and Equation 15)

(b) Power capability at rated and optimal voltage (Equation 11 and Equation 18)

Fig. 2: Comparison: Operation at rated voltage and at power-optimal voltage

Fig. 2a and Fig. 2b can be combined into one three-dimensional plot (Fig. 3), which summarises the concepts in a nice way. The coloured surface is displaying Equation 7 at $I = I_{\max}$. It can be observed how the pink curve stays on the 'mountain ridge', staying as high as possible towards the lower right corner.

Fig. 4 shows the consideration of the losses at maximal power. Fig. 4a displays the losses and Fig. 4b displays the efficiency, for both rated voltage and optimal voltage. It may be surprising to observe, that the losses for $l_P < l < l_{\max}$ are lower at rated voltage than at optimal voltage. Similarly, a higher efficiency can be observed for a large part of that length range. This can be explained with the fact, that the optimal voltage does not reduce losses or increase efficiency but it increases power capability. The good loss and efficiency numbers for operation at rated voltage beyond l_P at maximal power are mainly based on the fact that very little power can be transmitted.

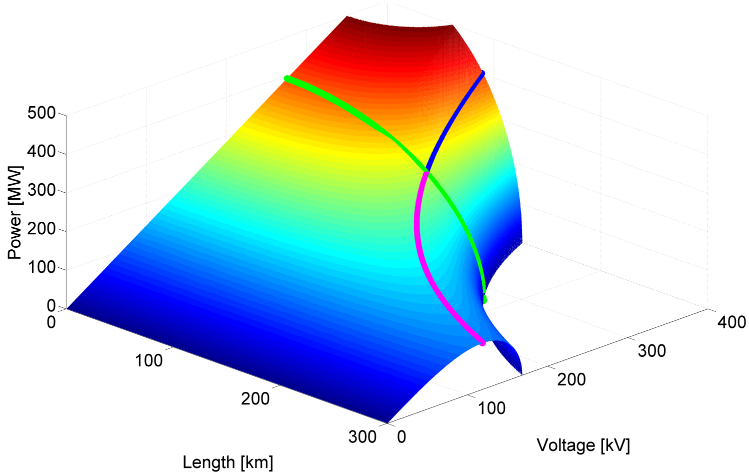
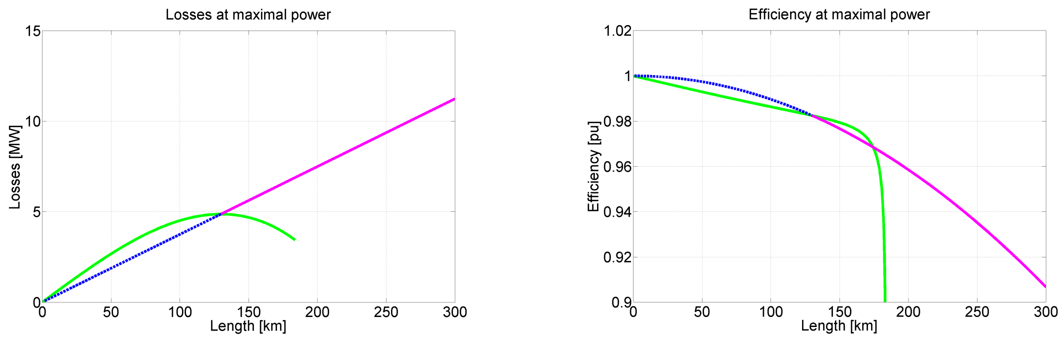


Fig. 3: Power transfer capability in 3D



(a) Active power losses at maximal power operation (Equation 12 and Equation 19)

(b) Efficiency at maximal power operation (Equation 14 and Equation 21)

Fig. 4: Comparison of the calculated losses at rated voltage and at power-optimal voltage

4.3. *Considerations regarding the Absolute Transmission Length Limit*

Equation 21 (or Equation 20) can be set to zero, to identify the maximal applicable transmission length at optimal voltage considering losses. This leads to the expression: $\frac{1}{2l_*} = \frac{2}{3}K_{\text{loss}}l_*$, which can be solved analytically, leading to:

$$l_{\text{max},U_P} = \sqrt{\frac{3}{4K_{\text{loss}}}}l_{\text{max}} \approx 982 \text{ km} \qquad \text{(for the example cable)} \tag{22}$$

Inserting Equation 22 into Equation 15 gives the voltage which can achieve the longest power transmission:

$$U_P(l_{\text{max},U_P}) = U_{\text{max}}\sqrt{\frac{2K_{\text{loss}}}{3}} \approx 36.4 \text{ kV} \qquad \text{(for the example cable)} \tag{23}$$

This indicates, that the achievable power transmission distance can be extended by a factor of ≈ 5.3 by reducing the voltage down to $\approx 13\%$. However, these calculated values for the example cable should not be taken as the real technical limit for power transmission on an HVAC cable. The introduced simplifications cannot be justified for cables of this length. It can however give indications on the possibilities beyond l_{max}.

5. Validation

The parameter $l_{\max}$ has been calculated without consideration of losses (Equation 3). This has been validated by setting Equation 13 to zero, leading to the expression: $\sqrt{1 - l_*^2} = K_{\text{loss}} \left(l_* - \frac{2}{3} l_*^3 \right)$, which has been solved numerically. The result $l_{\max,\text{num}} = 0.999962 \cdot l_{\max}$ shows that the maximal length at rated voltage can be obtained, without any problem, disregarding losses (only 7 m difference).

All expressions derived here are based on simplifications. It is therefore natural to question the validity of the results. To be able to assess the accuracy obtained with the simplified calculations, the calculated results are compared with results simulated with DIgSILENT PowerFactory. The numerical simulation model is based on a chain of eight pi-sections, and takes into account the aspects, that have been neglected for the analytical equations. Some calculations with distributed parameters have also been performed, proving the validity of the eight-pi-sections model.

When using the detailed PowerFactory model, which takes the voltage profile and voltage drop into account, operation at a specific voltage is not clearly defined anymore. It has been chosen to operate with fixed sending end voltage. Operating with fixed receiving end voltage leads to an over-voltage at the sending end. Fixing the voltage to the same value at both ends, by artificially suppressing the natural resistive voltage drop along the cable, leads to poor utilisation of the cable capabilities. These two other possibilities have been simulated, but the results are not very meaningful and they have not been included in this publication.

The example cable has $l_P = 130$ km and for any length shorter than that, the presented optimisation does not serve any purpose. The validation calculation has therefore been performed for $l_1 = 140$ km, $l_2 = 160$ km, $l_3 = 180$ km and $l_4 = 200$ km. The results of the analytical calculations and the numerical simulations have been summarised in Table 2. The optimal voltage has been identified with PowerFactory by trial and error.

Table 2: Accuracy comparison

Length	Method	$U_P(l)$	$P_{\text{trans}}(U_P, I_{\max}, l)$	$P_{\text{trans}}(U_{\max}, I_{\max}, l)$
140 km	Equations	255.3 kV	252.7 MW	249.3 MW
	PowerFactory	255.3 kV	261.5 MW	257.9 MW
	Error	0.0 %	-3.4 %	-3.3 %
160 km	Equations	223.4 kV	219.7 MW	187.3 MW
	PowerFactory	223.5 kV	229.7 MW	193.5 MW
	Error	-0.1 %	-4.4 %	-3.2 %
180 km	Equations	198.5 kV	193.9 MW	72.5 MW
	PowerFactory	198.8 kV	205.1 MW	34.4 MW
	Error	-0.3 %	-5.5 %	+110.8 %
200 km	Equations	178.7 kV	173.1 MW	———
	PowerFactory	179.0 kV	185.5 MW	———
	Error	-0.3 %	-6.7 %	———

The power-optimal voltage $U_P(l)$ can be calculated with high precision (error below 0.3 %) using Equation 15.

The power transfer capability at optimal voltage $P_{\text{trans}}(U_P, I_{\max}, l)$ can be calculated using Equation 20. The error in the example cases ranges from 3.4 % to 6.7 %, and the calculated values have in all four cases been below the reference. Equation 20 therefore gives a conservative estimation of the power transfer capability.

The power transfer capability at rated voltage $P_{\text{trans}}(U_{\max}, I_{\max}, l)$ can be calculated using Equation 13. The achieved precision is similar to using optimal voltage for $l_1 = 140$ km and $l_2 = 160$ km. However, for $l_3 = 180$ km, which is very close to the length limit $l_{\max} = 184$ km, the results are wrong. At the very limit, the simplifications used are not valid. This is however not critical, as it is not realistic to operate a HVAC cable so close to its limit (power factor $\cos(\phi) = 0.09$). For $l_4 = 200$ km, the calculation if of course not possible, since $l_4 > l_{\max}$.

The validation calculation indicates that the simplified equations somehow underestimate the power transfer capabilities of a cable. The achievable power transfer capability improvement has been calculated quite precisely. Since both power transfer capabilities (at rated voltage and at optimal voltage) are calculated somewhat below the actual value, the ratio between them can be quite accurate. The optimal operation voltage can be calculated quite precisely. The calculation errors are relevant, but they seem acceptable considering the motivation of this work.

6. Results

For any given cable type, the operation voltage which maximises the power transfer capability, is a function of the cable length; the longer the cable the lower the optimal voltage. The long distance properties of HVAC cables can be approximated with simple analytical equations, based on the introduced long-distance cable parameters. These parameters are displayed in Table 3. The nummerical values are given for the example cable.

Table 3: Long distance cable parameters

Parameter	Value	Unit	Equation	Description
l_P	130	km	Equation 16	length where operation at optimal voltage becomes possible
$l_{\max}$	184	km	Equation 3	length where operation at rated voltage becomes impossible
K_{loss}	2.63	%	Equation 4	Relation between power capability and losses

The implications on the operation of long HVAC cables are:

- For any cable with $l < l_P$, operation at optimal voltage is not possible due to limitations set by the cable insulation. The cable should be operated at rated voltage.
- For any cable with $l_P < l < l_{\max}$, voltage reduction increases power transfer capability, by avoiding excessive reactive currents.
- For any cable length beyond the maximal length at rated voltage ($l_{\max} < l$), voltage reduction is inevitable. The power transfer capability at rated voltage is zero.

It is natural to question the approach of reducing the operating voltage of a HVAC power cable rather than utilising another cable with a lower voltage rating. A lower-rated cable is less expensive and therefore appears as the better solution. However, the cable voltage rating influences the long distance power transmission capability, and this independently from the factual operating voltage.

Cables with lower voltage rating have a thinner insulation. This inevitably results in a larger cable capacitance. This larger capacitance causes higher reactive charging current, which leave less current capacity for the active current component. This reduction of the achievable active current reduces the power transfer capability, compared to a cable with higher voltage rating.

This phenomenon is displayed in Fig.5, where the power transfer capability of the example cable and three variations of it are compared. The data for the cable variations are also based on the manufacturer brochures [4] [5] [6] [7]. All four cables have identical operation voltage. The only difference is the voltage rating of the cables, which is set on the X-axis. The figure clearly shows, how cables with a higher voltage rating can transmit more power over long distance, even though the factual current and voltage amplitude are identical.

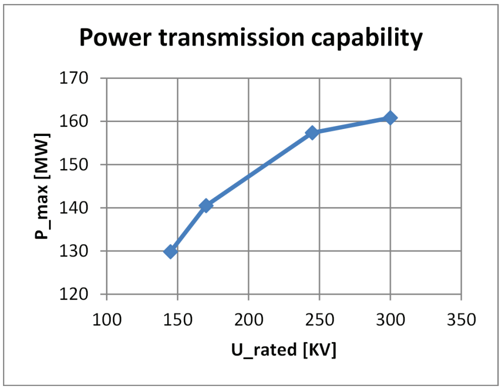


Fig. 5: Power transfer capability for four different cables at 132 kV operating voltage and 200 km length

7. Conclusion

Very long HVAC cables have received very little attention so far. This can easily be explained by the fact, that no existing HVAC cable is 'very long'. All existing HVAC cables are shorter than l_P. Operating at rated voltage always made sense until now, as optimising the operation voltage always was impossible due to insulation level limitations. However, considering the steady development towards longer cable projects, lengths beyond l_P are in reach. The theory developed here will gain relevance, at least in the long run. The simplified approach adopted here cannot lead to accurate results. It is however still useful:

- The physical relationships, expressed as analytical equations, display the main physical phenomena limiting the capabilities of very long HVAC cables, helping to get a better understanding of the subject.
- The here-introduced long distance cable parameter can easily be calculated based on the regular cable data. These parameters enable to get a better preliminary comparison of the long distance capabilities of different cables, rather than comparing the nameplate power rating. This can be interesting in the starting phase of a cable selection process.

The calculations have shown, that the operating voltage should be seen as a constrained parameter (constrained by the upper limit set by the insulation system). By optimising the operating voltage for a given cable, the viable power transmission distance at a given power can be significantly extended or the power transmission capability at a given distance can be increased.

For very long HVAC cable projects, it makes sense to consider cables with very high voltage rating, even though they might not be operated at full voltage. The increased insulation thickness lowers their capacitance, making these cables better suitable for very long distance transmission. The results highlight the importance of HVAC cables with low capacitance for very long distance applications.

However, increasing the insulation thickness does not only enable for increased voltage ratings. It can also be seen as it lowers the stress on the insulation material (when voltage rating is kept constant). This can possibly open for the utilisation of new insulation material specialised for low-permittivity. This might become a new niche market of specialised cables.

References

[1] Patrick Smith. Siemens looks to recover offshore wind HVDC losses. Wind Power Offshore. 2015
[2] Total homepage. Powering the Martin Linge field from shore, accessed on 2016-04-26.
[3] CIGRE Working Group B1.40. Offshore generation cable Connection. Cigr report 610 , February 2015, ISBN : 978-2-85873-311-8
[4] ABB's high voltage cable unit in Sweden. XLPE Land Cable Systems - User's Guide, Rev 5. 2010
[5] ABB's high voltage cable unit in Sweden. XLPE Submarine Cable Systems - Attachment to XLPE Land Cable Systems - User's Guide, Rev 5. 2010
[6] nkt cables GmbH. High Voltage Cable Systems - Cables and Accessories up to 550 kV.
[7] Prysmian Cables & Systems. High Voltage Cables.
[8] Insulated Conductors Committee - Task Group 7-39, Cost of Losses, Loss Evaluation for Underground Transmission and Distribution Cable Systems. IEEE Transactions on Power Delivery, Vol. 5. No. 4. 1990

Acknowledgements

This activity has been funded by the Norwegian Research Centre for Offshore Wind Technology NOWITECH.