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Variable Transmission Voltage for Loss Minimization in Long Offshore Wind Farm AC Export Cables

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***Abstract*—Connection of offshore wind farms to shore requires the use of submarine cables. In the case of long HVAC connections, the capacitive charging currents limit the transfer capability and lead to high losses. This paper shows that the losses can be substantially reduced by continuously adjusting the cable operating voltage according to the instantaneous wind farm power production. Calculations for a 320 MW wind farm connected to shore via a 200 km cable at 220 kV nominal voltage shows that an annual loss reduction of 9% is achievable by simply using a ±15% tap changer voltage regulation on the two transformers. Allowing a larger voltage regulation range leads to further loss reduction (13% for 0.4-1.0 p.u. voltage range). If the windfarm has a low utilization factor, the loss reduction potential is demonstrated to be as high as 21%. The methodology can be applied without introducing new technology that needs to be developed or qualified.**

***Index Terms*— Wind energy, wind farm, offshore wind, submarine cable, power engineering computing, export cable, cable connection, operation, voltage control, losses, optimization.**

I. INTRODUCTION

Most offshore wind farms are connected to the onshore grid via HVAC cables. As it is often desirable to locate the wind farm at long distances from shore, e.g. due to more favorable wind conditions, the increased losses in the HVAC cables that result from charging currents can make the development of the wind farm economically or even technically infeasible. This limitation for long HVAC cables has motivated the use of HVDC connections to shore. The HVDC solution gives lower losses but represents a step in investment and operating cost [1]-[5].

The increased cost and complexity of HVDC solutions has motivated a search for methods to extend the feasibility of the HVAC alternative. One possibility is to introduce reactive shunt compensation at one or more positions along the cable but such solution requires either sub-sea compensation equipment or additional offshore platforms. Another alternative is to use a lower frequency than the standard 50/60 Hz frequency [6], thereby reducing both charging currents and skin effect in the conductors. One important disadvantage of the low-frequency AC alternative is the need of specialized components that has not yet been qualified for this use. Other disadvantages are the increased weight and volume of the magnetic components as well as the need for an onshore converter station.

In this work, we propose an alternative solution, which is entirely based on existing 50/60 Hz AC technology. This solution is motivated by the observation that the cable losses associated with the cable charging currents decrease with decreasing voltage. That way, the total losses in the cable can be reduced when the wind farm production is low since the losses associated with charging currents may dominate over those of the transmitted power. By varying the operating voltage of the export cables by transformer on-line tap changers, we show that it is possible to both reduce the cable losses and to extend the technical range limits of the AC cable. Two strategies are investigated. 1) Operating at a fixed, optimized voltage, or 2) operating at variable voltage that is continuously optimized for the instantaneous wind farm production. The two operating strategies are compared using wind farm power production and cable length as parameters. Finally, the potential reduction in annual losses are determined by considering the distribution of the wind farm production over one year of operation. The results are shown for two alternative distribution profiles.

II. SYSTEM OVERVIEW

This study considers a system consisting of an aggregated wind farm that is connected to land grid via an AC cable as shown in Fig. 1. The cable operating voltage is controlled by the interfacing transformers that are assumed to have on-line tap-changers. The tap-changer is adjusted based on the wind farm active power production. Reactive compensation is provided by the indicated shunt reactors and/or the onshore grid and wind farm.

The study is based on a 220 kV cable whose electrical parameters and current rating are listed in Table I [2].

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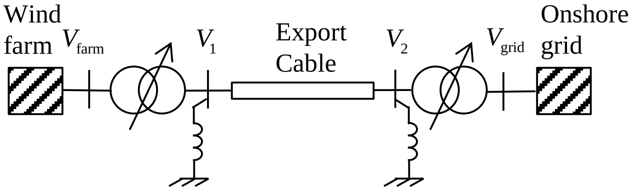

Fig. 1. Connection of wind farm to shore.

TABLE I.
CABLE PARAMETERS (50 HZ) AND CHARACTERISTICS [2].

Nominal voltage	220 kV
Cable section [mm^2]	1000
R [Ω/km]	0.048
L [mH/km]	0.37
C [µF/km]	0.18
G [S/km]	0
Nominal current [A]	1055

III. SYSTEM LEVEL MODELING

The system in Fig. 1 is represented by the electrical circuit depicted in Fig. 2 that is assumed to operate at 50 Hz. An aggregated representation by voltage sources is used for the systems on the grid-side and offshore side of the cable.

- The onshore grid voltage is assumed fixed and equal to its nominal value (e.g. 380 kV).
- The grid connection transformer is assumed ideal with voltage ratio k. The cable onshore voltage is therefore

$$V_2 = k \cdot V_{\text{grid}} \tag{1}$$

- The onshore grid and the onshore transformer with tap-changer are modelled by the ideal voltage source V_2. The effect of the tap-changer is represented by varying the amplitude of the voltage source V_2.
- The wind farm connection transformer is also assumed ideal. The voltage on the cable side is allowed to exceed the cable voltage on the cable onshore side by 10%. The permissible operating area is specified as

$$V_1 = V_2 \cdot \alpha \cdot e^{j\beta} \tag{2}$$

  where $\alpha \in [1, 1.1]$. α is the ratio between the voltage amplitude at the farm side and grid side ends of the cable. β is the difference in phase angle (radians) between the voltage at the two ends.
- It is assumed that the reactive power consumption can be controlled such that the cable wind farm side voltage (V_1) in (2) is within the permissible range. The voltage source V_1 represents the aggregated effect of tap-changer, transformer, wind turbine converters and reactive power compensation equipment.
- The cable is represented by its exact PI-equivalent, accurately taking into account the distributed parameter effects and thereby the variation of voltage and current along the cable. The details are shown in Section IV.

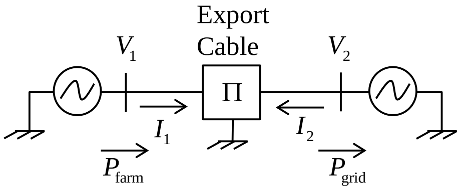

Fig. 2. Electrical equivalent with cable represented by exact pi-equivalent.

IV. CABLE MODELING

A. Cable Terminal Admittance Matrix

The cable behavior is defined by its length l, its per-unit-length (PUL) series impedance Z and shunt admittance Y,

$$Z = R + j\omega L \tag{3}$$

$$Y = G + j\omega C \tag{4}$$

From the PUL parameters, the cable admittance matrix is obtained as [7]

$$\mathbf{Y}_{\Pi} = \left[\begin{array}{c:c} \dfrac{\coth(\gamma l)}{Z_C} & \dfrac{-1}{Z_C \sinh(\gamma l)} \\ \hdashline \dfrac{-1}{Z_C \sinh(\gamma l)} & \dfrac{\coth(\gamma l)}{Z_C} \end{array}\right] \tag{5}$$

where

$$Z_C = \sqrt{\frac{Z}{Y}} \tag{6}$$

$$\gamma = \sqrt{ZY} \tag{7}$$

Using the admittance matrix (5) together with the (known) terminal voltages, the cable terminal currents are calculated as

$$\begin{bmatrix} I_1 & I_2 \end{bmatrix}^T = \mathbf{Y}_{\Pi} \begin{bmatrix} V_1 & V_2 \end{bmatrix}^T \tag{8}$$

B. Cable Loss Calculation

From the solution of currents at the cable ends, the cable active and reactive power transmitted from the wind farm (farm) and absorbed at the land side (grid) are calculated as

$$P_{\text{farm}} = \sqrt{3}\,\mathrm{Re}\{V_1 I_1^*\}, \quad Q_{\text{farm}} = \sqrt{3}\,\mathrm{Im}\{V_1 I_1^*\} \tag{9a}$$

$$P_{\text{grid}} = -\sqrt{3}\,\mathrm{Re}\{V_2 I_2^*\}, \quad Q_{\text{grid}} = -\sqrt{3}\,\mathrm{Im}\{V_2 I_2^*\} \tag{9b}$$

and the cable losses are obtained as

$$P_{\text{loss}} = \sqrt{3}\,\mathrm{Re}\{V_1 I_1^* + V_2 I_2^*\} \tag{10}$$

C. Cable Internal Voltages and Currents

In order to assess the voltage and current at (N–1) internal nodes, the cable is subdivided into N segments of equal length $l_{\text{seg}}=l/N$ as shown in Fig. 3. The admittance matrix is calculated by (5) with length l_{seg}, and the global admittance matrix is assembled using nodal analysis. With the voltages at the two cable ends taken as known quantities, the internal voltages and currents are calculated using nodal analysis. This method is used for monitoring the voltage and current along the cable. The segmentation could also be used for taking into account variations in cable parameters along the route, e.g. variations in resistance due to temperature variations.

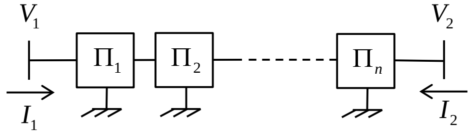

Fig. 3. Segmentation of cable into *n* sections for assessment of internal voltages and currents.

V. CABLE EFFICIENCY AND POWER TRANSFER LIMIT

A. Definition

The objective is to operate the system in such way that the cable efficiency is maximized, defined as the ratio between transmitted power to the grid (P_{grid}) and the produced power at the wind farm (P_{farm}) (11),

$$\eta = \frac{P_{\text{grid}}}{P_{\text{farm}}} \tag{11}$$

It is remarked that since we have $P_{\text{loss}} = P_{\text{farm}} - P_{\text{grid}}$, it follows that for a given instantaneous wind power production, operation at maximum cable efficiency is equivalent to operation with minimum cable losses.

To analyze the efficiency, we start by rewriting (8) as

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} A & B \\ B & A \end{bmatrix} \cdot \begin{bmatrix} \xi V_2 \\ V_2 \end{bmatrix} \tag{12}$$

where ξ is the voltage scaling required for achieving a given active and reactive power flow,

$$\xi = \alpha \cdot e^{j\beta} \tag{13}$$

In (12), *A*, *B* and ξ are complex quantities while V_2 can be assumed real-valued. Combining (12) with the expressions for power in (9) gives

$$\begin{aligned} P_{\text{farm}} &= \sqrt{3}\,\mathrm{Re}\{\xi V_2 (A\xi V_2 + BV_2)^*\} \\ &= \sqrt{3}\,\mathrm{Re}\{\xi(A\xi + B)^*\} V_2{}^2 \end{aligned} \tag{14a}$$

$$\begin{aligned} P_{\text{grid}} &= -\sqrt{3}\,\mathrm{Re}\{V_2 (B\xi V_2 + AV_2)^*\} \\ &= -\sqrt{3}\,\mathrm{Re}\{\xi(B\xi + A)^*\} V_2{}^2 \end{aligned} \tag{14b}$$

and for the cable efficiency

$$\eta = \frac{P_{\text{grid}}}{P_{\text{farm}}} = -\frac{\mathrm{Re}\{\xi(B\xi + A)^*\}}{\mathrm{Re}\{\xi(A\xi + B)^*\}} \tag{15}$$

It is noted from (15) that the cable efficiency, including its maximum value, is independent of the operating voltage V_2. For a given efficiency, the operating voltage V_2 determines the power that is transmitted.

Fig. 4 shows the cable efficiency η for the 220 kV cable with parameters as given in Table I. The efficiency is shown as function of the scale angle β in (13) with unity scaling (α=1), for alternative cable lengths. It is seen that for each cable length, there exists a unique scale angle that maximizes the efficiency. The maximum achievable efficiency decreases with the cable length. The operating voltage V_2 has no effect on the maximum achievable efficiency.

It is remarked that the longest cables can only be operated with a low voltage V_2 since the charging currents will otherwise cause the rated current to be exceeded at the cable ends. Therefore, the power transfer capability is very much reduced, making such lengths economical unfeasible. In this work, we will instead focus on the cable efficiency in the case of moderate cable lengths. The maximum transfer capability is studied separately in Section VIII-H.

B. Voltage Control for Optimal Efficiency

In the case of long cables, the cable efficiency can be further improved by also controlling the scaling factor α, in addition to the angle β. Fig. 5 shows the efficiency η as function of β with the scaling α as parameter, for a cable length of 200 km. For the given cable and length, the efficiency can never exceed η_{opt}=0.94 which represents a theoretical upper limit for this cable parameter set. From the results in Fig. 4 and 5, we can conclude that for a given cable type and length, there exists a scaling $\xi = \alpha \cdot e^{j\beta}$ that optimizes the cable operation in terms of cable efficiency. Both α and β should therefore be used for controlling the cable operation, which is the principle used in this work. It is remarked that the optimum value for α approaches 1.0 as the cable length is reduced while β approaches zero. This is as expected since it follows from (2) that α = 1.0 and β = 0 implies that voltage at each end of the cable has the same amplitude and zero phase difference. This will necessarily have to be the case when the cable length approaches zero.

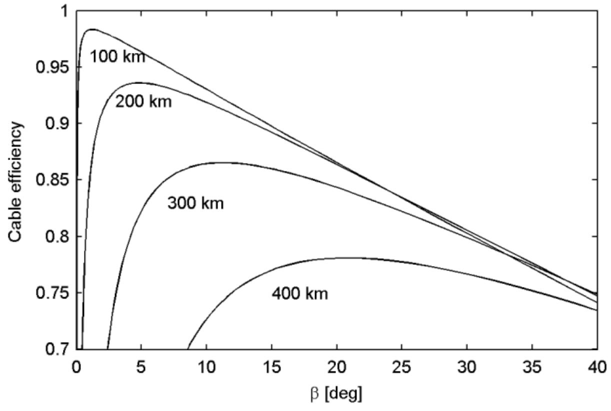

Fig. 4. Cable efficiency as function of wind farm voltage scaling, $\xi = 1 \cdot e^{j\beta}$ for different cable lengths.

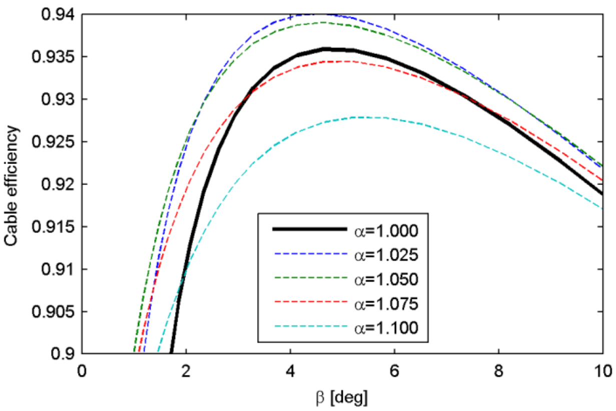

Fig. 5. Cable efficiency of 200 km cable as function of wind farm voltage scaling, $\xi = \alpha \cdot e^{j\beta}$.

The loss contributions can be understood by use of a simplified cable model [10]. Here, one assumes that the voltage is constant along the cable so that the charging current is in quadrature with the (active) transmission current, and that one has 50% reactive compensation on each end. For this situation, the associated charging current losses and transmission current losses are plotted in Fig. 6, expressed as MW loss per produced MW. The result is shown for two alternative operating voltages, 1.0 p.u. and 0.4 p.u. of 220 kV. It is observed that in each case the total loss has a minimum when the reactive losses are equal to the transmission losses. It is further seen that the two minima are practically equal, corresponding to a common maximum value for the cable efficiency. The accuracy of this simplified modeling procedure is discussed in Section VIII-I.

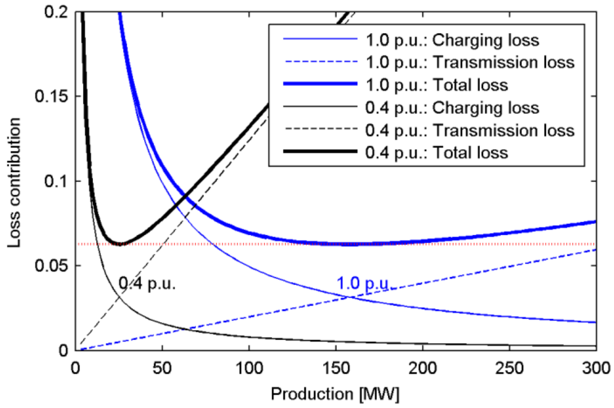

Fig. 6. Loss contribution from reactive power and active power, expressed as $P_{\text{loss}}/P_{\text{farm}}$. Calculated with simplified method described in [10].

C. Optimal Operating Voltage

For a given cable type and length, one can identify the scaling ξ_{opt} which corresponds to the best point in Fig. 5, and then establish a curve which relates the (optimum) operating voltage V_2 to the wind farm instantaneous power production,

$$V_{2,\text{opt}} = f(P_{\text{farm}}, \xi_{\text{opt}}) . \qquad (16)$$

Matlab™ has been used to find the optimum voltage for each wind farm production level. A pseudocode for the determination of $V_{2,\text{opt}}$ is defined by the itemized list in Fig. 7.

```
1. Read cable length and cable parameters and establish the cable admittance matrix $\mathbf{Y}_{\Pi}$ according to (5).
2. Use (8) and (12) to determine $A$ and $B$ in (12).
3. Use Matlab™ optimization routine fmincon to find $\xi_{\text{opt}}$ that maximizes the efficiency $\eta$ expressed in (15), together with (13) and the constraints $\alpha \in [1, 1.1]$ and $\beta \in [-\frac{\pi}{2}, \frac{\pi}{2}]$ .
4. Loop through the relevant values for $P_{\text{farm}}$ and use (14a) and $\xi_{\text{opt}}$ to determine the optimum voltage $V_{2,\text{opt}}$ that for each specific $P_{\text{farm}}$ maximizes the efficiency.
```

Fig. 7. Pseudocode for determination of operating voltage for maximum efficiency for each level of wind farm production.

The result is shown in Fig. 8 for the best point ξ_{opt} which is found to be α=1.025, β=4.5° for the 200 km cable with parameters specified in Table 1. The same efficiency (0.94) applies for the entire curve in Fig. 8, being independent of the wind farm power production. It is however observed that as the wind farm production increases, the maximum permissible operating voltage (V_2=1.0 p.u.) becomes exceeded at about 170 MW, and the current limit (1055 A) becomes exceeded at about 250 MW as indicated by the asterisk.

In order to operate the cable at such high power transfers, it therefore becomes necessary to modify the choice of operating voltage V_2 and voltage scaling ξ. In the next sections we will achieve this by searching for the combination of V_2, α, and β which satisfies the required production without exceeding the permissible limits on cable voltage and current, while maximizing the cable efficiency.

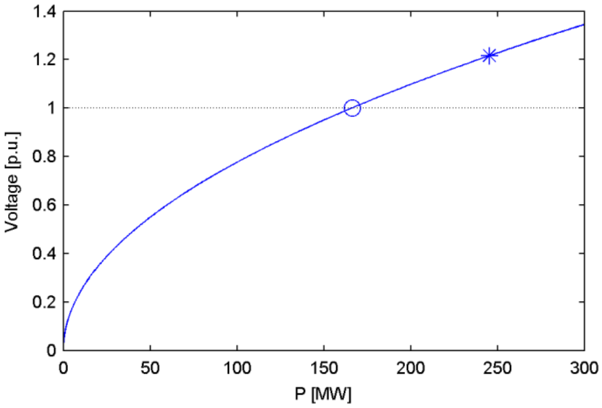

Fig. 8. Optimal cable operating voltage V_2 as function of wind farm instantaneous production P_{wf}, for maximum efficiency for the 200 km cable. The asterisk and circle denote the operating voltage V_2 at which the cable rated current and rated voltage are exceeded, respectively.

D. Maximum Power Transfer

In addition to allowing optimal efficiency, the control of α *also* permits to increase the cable power transfer capability.

Fig. 9 shows the maximum power that can be transmitted as function of α with β being free to vary. It is observed that the transfer capability increases from 190 MW to 300 MW when α increases from 1.0 to 1.06.

Fig. 10 shows the current on the two cable ends associated with the voltage control in Fig. 9. With α=1.0, the current limit (1055A) is reached on the wind farm end with the current on the grid side being only about 700 A. By increasing α, the current increases on the grid side until it eventually reaches the current limit at α=1.06, which represents the maximum power transfer limit in Fig. 9. This result is explained as follows. The initial reactive current distribution is uneven when α=1.0 because a reactive current component is forced to flow between the two cable ends to cancel out the voltage drop along the cable which is associated with the active current flow through the series impedance. By increasing the feeding end voltage, the need for this reactive current component is reduced and eventually eliminated.

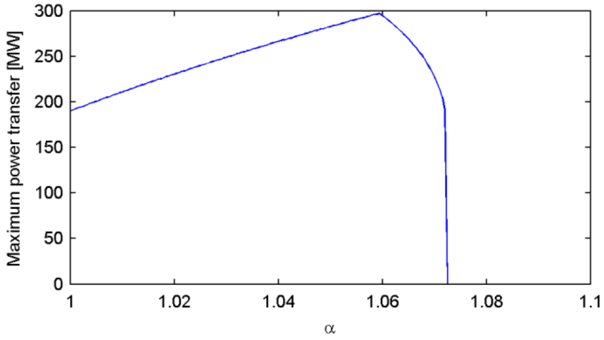

Fig. 9. Maximum power transfer capability with given α. (200 km cable).

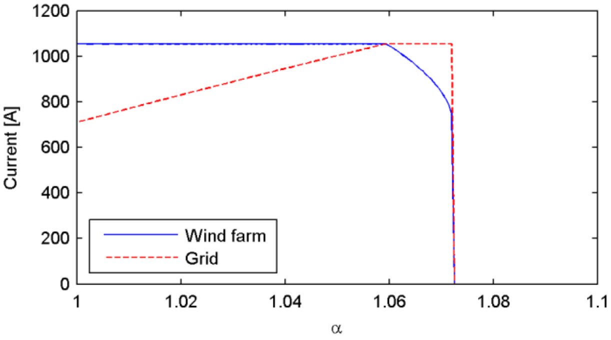

Fig. 10. Current on cable ends at maximum power transfer.

VI. OPERATING STRATEGIES

A. Fixed Transmission Voltage

One possible operating principle is to use a fixed voltage V_2 which may be lower than the nominal voltage.

Fig. 11 shows the cable efficiency as function of the wind farm production with alternative operating voltages V_2 in p.u. of the nominal voltage, for a cable length of 200 km. The results are shown up the point where the required power transfer becomes technically infeasible as the current limit is exceeded. Clearly, the fixed operating voltage should be chosen based on the expected production level, with lower voltage for low production levels. It can be seen from Fig. 11 that operation at a voltage lower than rated will become beneficial as soon as the production is less than what gives maximum efficiency for operation at 1.0 pu (about 180 MW for the 200 km cable). Below this point, the losses related to charging currents will dominate (Fig.6). Therefore, the total losses can be reduced by reducing the operating voltage.

B. Variable Transmission Voltage

A better strategy is to operate the cable with a variable transmission voltage V_2 that is chosen based on the instantaneous wind farm production. In this case, it is necessary to determine the voltage that gives the lowest cable losses for each production level while not exceeding the voltage and current limits.

Fig. 12 shows the optimum cable voltage as function of the wind farm production, assuming that the operating voltage is permitted to vary in the range 0.4 p.u.-1.0 p.u. The result is shown for cable lengths 100 km, 200 km and 300 km. It is seen that the optimum voltage decreases as wind farm production is reduced, consistently with the result in Fig. 8.

The corresponding cable efficiency is shown in Fig. 13 with solid traces. For comparison, the result with 1.0 p.u. (fixed) operating voltage is shown with dashed traces. It is observed that use of a variable transmission voltage can greatly increase the cable efficiency in periods where wind farm production is low. In the case of the 300 km length, the dashed trace is missing since operation at 1.0 p.u. is not feasible as the current limit is exceeded already at very low production.

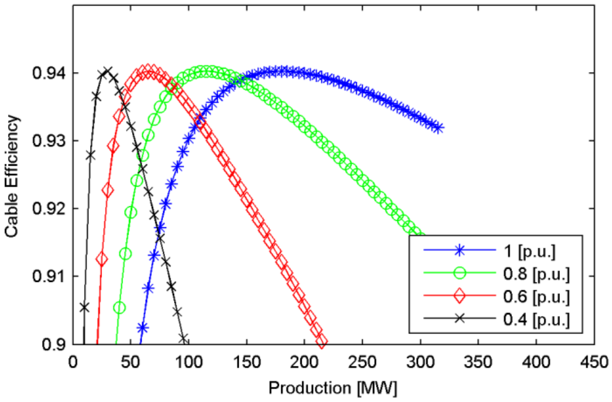

Fig. 11. Cable efficiency for 200 km cable as function of wind farm instantaneous active power production. Parameter: Cable operating voltage V_2.

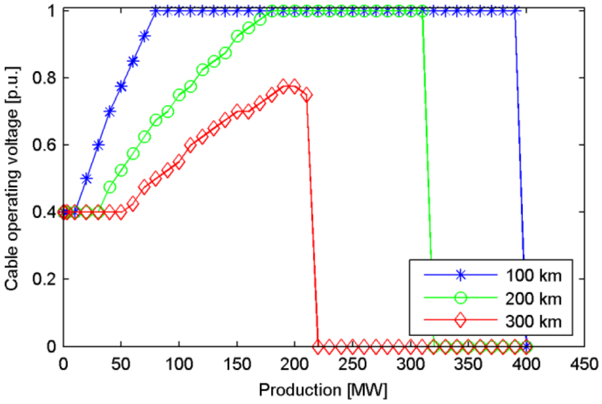

Fig. 12. Optimal cable operating voltage as function of wind farm instantaneous active power production. Parameter: cable length.

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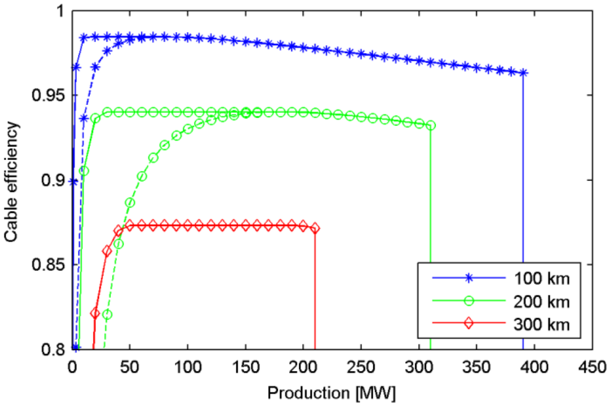

Fig. 13. Cable efficiency as function of wind farm instantaneous active power production. Solid lines: Operation at optimal (variable) voltage. Dashed lines: operation at 1.0 p.u. fixed voltage. Parameter: cable length.

VII. Loss Minimization With Representative Distribution of Annual Wind Farm Production

A. *Wind Farm Annual Production*

The advantages of using a reduced, fixed operating voltage, or a variable operating voltage, are dependent on the wind farm production profile. In order to quantify the advantage we make use of the annual efficiency defined as

$$\eta_{\text{annual}} = \frac{\sum_{i=1}^{N} \Delta t_i P_{\text{grid},i}}{\sum_{i=1}^{N} \Delta t_i (P_{\text{farm},i} + P_{\text{curtail},i})} \tag{17}$$

The term $P_{\text{curtail},i}$ in (17) represents curtailment due to lack of cable capacity. Thus, any wind energy that is not produced due to lack of transfer capacity is treated as losses in the following calculations.

B. *Example: Wind Farm With High Utilization Factor*

As an example we consider the ten-year distribution of the power production of a windfarm. This example is a synthesized power production for the NOWITECH reference wind farm [8] which is considered representative for a wind farm at Doggerbank in the North Sea.

Fig. 14 shows the relative duration of the wind farm production with a resolution of N=100 points. The capacity utilization factor for this data set is 0.46, defined as the average annual energy production divided by the theoretical maximum annual production (rated production year around, no curtailment).

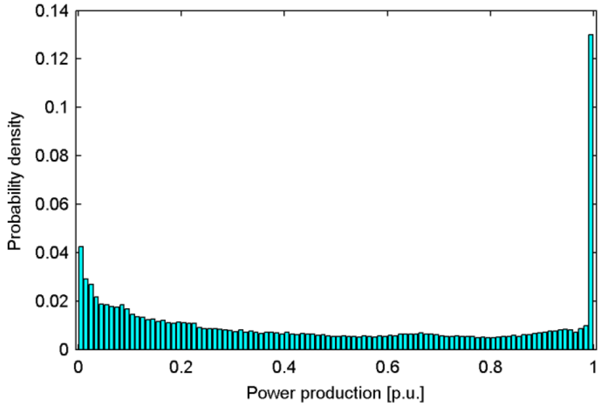

Fig. 14. Distribution of wind farm power production in [p.u.] of maximum installed windfarm production. Data for wind farm with high utilization factor.

Fig. 15 shows the annual cable efficiency calculated by (17) as function of the installed power at the wind farm, assuming that the distribution in Fig. 14 is independent of the installed production. The annual efficiency is shown for alternative operating conditions for the cable: Operating with a fixed voltage, or operating with a variable voltage in the range 0.4-1.0 p.u. It is observed that a fixed operating voltage should be chosen based on the installed power. The maximum achievable annual efficiency is anyhow limited to about 0.925. It is further observed that by allowing the voltage to vary in the range 0.4-1.0 p.u., the annual efficiency can be increased to nearly 0.94 for a wide range of installed powers, being close to the theoretical upper limit of 0.94 in Fig. 5. With P_{farm}=320 MW, the increase of annual efficiency is somewhat lower, from about 0.925 to 0.935 compared to operating at 1.0 p.u. fixed voltage.

C. *Loss Reduction Utilizing Tap Regulation*

Transformers with online tap changers (OLTC) can be used to adapt the operating voltage to the instantaneous wind farm production. That way, the cable efficiency can be improved compared to the operation with fixed voltage shown in Fig. 15.

Fig. 16 shows the cable efficiency curves corresponding to those in Fig. 15 when assuming that the transformers have OLTC capability of ±15%. The result is shown with dashed traces when the nominal tap setting is 0.4, 0.6, or 0.87 p.u. The corresponding result with fixed voltage is shown with solid traces. Comparison between solid and dashed traces in Fig. 12 shows that utilizing the transformer voltage regulating capability of ±15% can improve the cable efficiency with almost 1%.

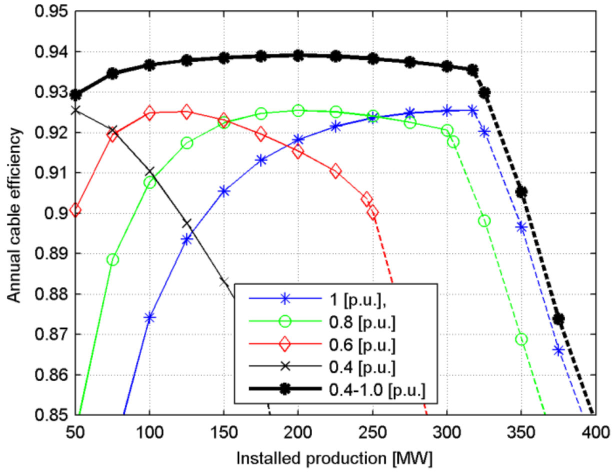

Fig. 15. Annual cable efficiency as function of wind farm maximum instantaneous production. The dashed portion of traces represents wind farms that can produce more than cable maximum capacity such that production curtailment will be required (causing the steep drop in annual efficiency).

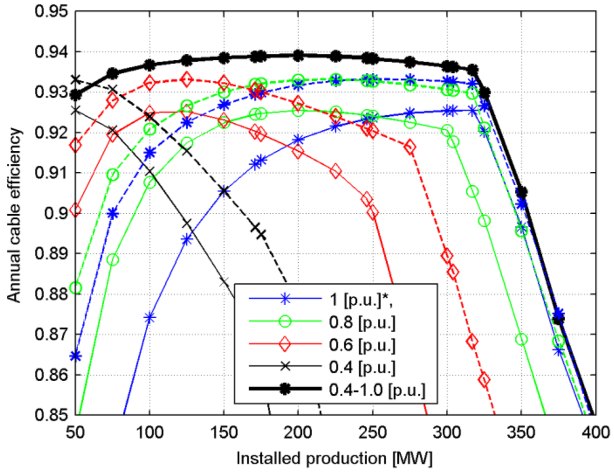

Fig. 16. Annual cable efficiency as function of wind farm maximum instantaneous production with cable operating voltage as parameter. The result with ±15% regulating capability is shown with dashed traces. The two traces with asterisk, (blue) are a special case for which the solid trace is operation at 1.0 p.u. and the dashed trace is operation at 0.87 p.u ±15% such that the maximum voltage becomes 0.87·1.15=1.0 p.u.

D. System Expansion

Wind farms can be built in successive steps such that the power transmission is initially less than the cable transfer capability. In such scenario, it will be beneficial to be able to operate the cable at both 1.0 p.u. and at a substantially reduced voltage. As an example, consider the situation that the wind farm is being developed in two stages where an initial installation of 150 MW is increased to 300 MW. In this case, it is desirable to be able to achieve high efficiency at both 150 MW and 300 MW installed production.

Fig. 17 shows the cable efficiency as function of installed farm production, with alternative voltage variation ranges with OLTC. It is observed that it is desirable to have a quite large voltage variation range in order to allow a high efficiency also at 150 MW. For instance, allowing 0.6-1.0 p.u. variation in the voltage improves the cable efficiency at 150 MW installed power by 2.5% compared to operation with 1.0 p.u. fixed voltage, and by about 1% at 300 MW installed power. Table II lists the percent voltage variations associated with the ranges in Fig. 17. It is for instance seen that a 0.6-1.0 p.u. voltage variation implies a nominal voltage ratio of 0.8 p.u. with a ±25% regulation.

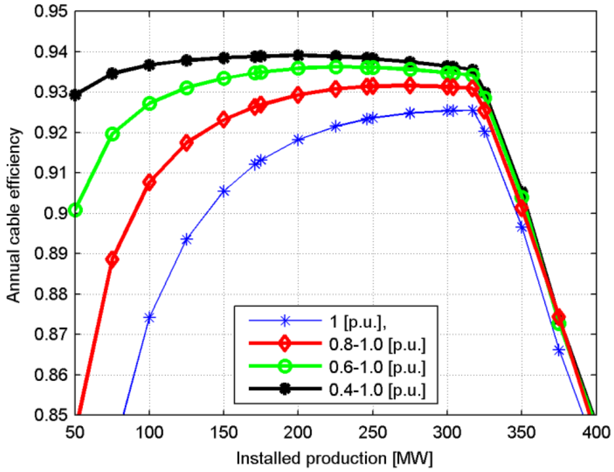

Fig. 17. Annual cable efficiency as function of wind farm maximum instantaneous production for different voltage regulation intervals.

TABLE II.
VOLTAGE REGULATION RANGES IN FIG. 17.

Range	Nominal voltage	Variation
0.8-1.0 p.u.	0.9 p.u.	±11.1 %
0.6-1.0 p.u.	0.8 p.u.	±25.0 %
0.4-1.0 p.u.	0.7 p.u.	±42.9 %

VIII. DISCUSSION

A. Loss Reduction Potential

The results in Sections VI and VII show that there is a significant potential for increased annual cable efficiency and consequently reduced losses. It is important to realize that what appears to be a small increase in efficiency actually represents a large reduction in losses and consequently a large reduction in associated costs. For instance, an increase of the efficiency from η=0.92 to η_{opt}=0.93 implies a loss reduction of 12.5% since the reduction ΔP_{loss} in percent is

$$\Delta P_{\text{loss}} = 100\frac{(1-\eta_{\text{opt}})P_{\text{farm}} - (1-\eta)P_{\text{farm}}}{(1-\eta)P_{\text{farm}}}\ \% \tag{18}$$

Table III summarizes the loss reduction potential for some selected cases for the wind farm with high utilization factor. The content in the tables are based on readouts from the presented plots. The reference case for the table is operation of cable at fixed rated voltage (1.0 p.u.).

TABLE III.
SAMPLES OF ANNUAL LOSS REDUCTION POTENTIAL FOR THE 200 KM TRANSMISSION FOR WIND FARM WITH HIGH UTILIZATION FACTOR

Wind farm rating [MW]	Operation	Annual efficiency improvement	Percent reduction in annual losses
320	Variable voltage 0.4-1.0 p.u.	0.925 ⟶ 0.935	13%
320	Variable voltage	0.925 ⟶ 0.932	9%

	0.87 p.u. ±15%		
200	Fixed voltage 0.8 p.u.	0.92 ⟶ 0.925	6%
200	Variable voltage 0.8 p.u. ±15%	0.92 ⟶ 0.932	15%
200	Variable voltage 0.4-1.0 p.u.	0.92 ⟶ 0.94	25%

B. Tap-Changer

In this work, it is assumed that the tap-changers have infinitely small steps and that there are no limitations in how often they are allowed to be operated. In reality, there will be a limited number of steps and one will most likely have to restrict how often the tap-changers are operated in order to limit the wear-and-tear. This will give a somewhat smaller reduction in losses but it is not believed to have significant impact on the results since the fluctuations in power production for a windfarm are rather slow.

Transformers with on-line tap changers are more complex and will probably be somewhat less reliable than transformers without. This is an aspect that needs to be taken into account when considering operation with variable operating voltage. For instance, proper protection against overvoltage is essential for ensuring the reliability of transformers with tap-changers.

It is acknowledged that a voltage regulation of 0.4-1.0 p.u. is very high. It was included in the analysis in order to reveal the full potential of voltage regulation. There are however, examples of power transformers in use with a quite large regulation range. One example is the third pole of the Skagerak HVDC connection where the transformer voltage regulation is +30/–10% [9]

C. Wind Farm Utilization Factor

The calculated results in Section VII demonstrated that allowing regulation of the operating voltage allows substantial improvements to the cable efficiency when taking into account the annual distribution of the wind farm production. That result was for a specific case with high utilization factor. In the case of wind farm with lower utilization factors, the improvements to cable efficiency are even higher. Fig. 18 shows the relative duration of the wind farm annual production of such a case where the utilization factor is 0.35. Compared to the previous distribution in Fig. 14 that has a utilization factor of 0.46, the average production relative to maximum installed power is lower. Fig. 19 shows the annual cable efficiency associated with this power distribution. As expected, the annual efficiency is with fixed operating voltage lower than in the case of high utilization factor (Fig. 15) whereas the annual efficiency in Figs. 15 and 19 are almost equal when using the 0.4-1.0 p.u. voltage variation. It can therefore be concluded that the value of operating at variable voltage increases with decreasing utilization factor.

Table IV summarizes the loss reduction potential for two cases for the wind farm with low utilization factor. The reference case for the table is operation of cable at fixed rated voltage (1.0 p.u.).

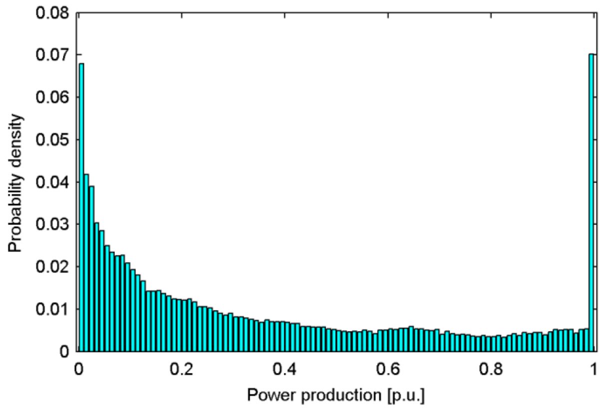

Fig. 18. Distribution of wind farm annual power production in [p.u.] of maximum installed production. Data for wind farm with low utilization factor.

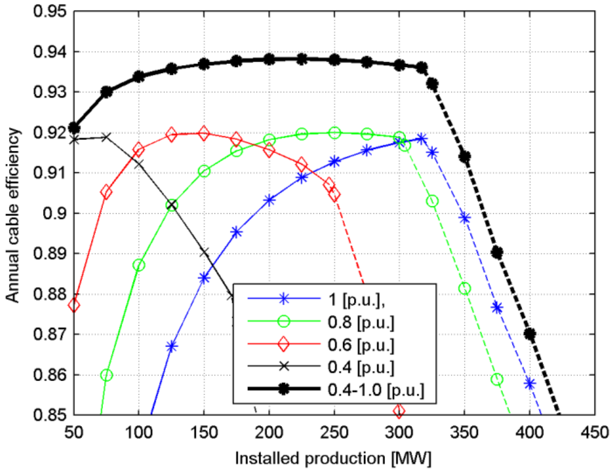

Fig. 19. Annual cable efficiency as function of wind farm maximum instantaneous production. Wind farm with low utilization factor. The dashed traces represent situation with curtailment of production.

TABLE IV.
SAMPLES OF ANNUAL LOSS REDUCTION POTENTIAL FOR THE 200 KM TRANSMISSION FOR WIND FARM WITH LOW UTILIZATION FACTOR

Wind farm rating [MW]	Operation	Annual efficiency improvement	Percent reduction in annual losses
320	Variable voltage 0.4-1.0 p.u.	0.918 ⟶ 0.935	21%
200	Fixed voltage 0.8 p.u.	0.903 ⟶ 0.92	18%

D. Cable Length and Cable Design Parameters

Most calculated results assumed a cable length of 200 km. This choice was based on the fact that few wind farm installations exist with more than 100 km connection length. It is therefore a need for new operating principles and/or technologies to make AC transmission beyond the 100 km distance viable, and this work is a contribution in that direction.

The analysis also considered one specific cable design. It is clear, however, that the cable electrical per-unit-length parameters (*R*, *L*, *C*) are dependent on the cable design, giving additional instrument to be included in the optimization.

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E. Cable Temperature Variation

The cable is in the analysis represented by a distributed-parameter model to properly take into account the variation of losses along the cable associated with the charging currents. However, it is assumed that the AC resistance is constant along the cable, thereby ignoring the temperature variation along the cable. This assumption will have some influence on the numerical values, but is not believed to have major impact on the relative reduction in losses when operating at optimal voltage. Such temperature variation can be easily included in the analysis by segmentation of the cable as shown in Fig. 3.

F. Other System Losses

This work focuses on the losses in the cable only. It is clear that operation at a reduced voltage will also affect the losses in in other system parts, e.g. the two transformers and compensation reactors. Transformer losses are low compared to the losses of very long cables and are not expected to have a significant impact on the conclusions.

If the losses in the compensation reactors had been included in the calculations, the total efficiency improvement would have been somewhat higher since the losses in the reactors increase with the square of the operating voltage. The reactor annual losses will therefore become significantly lower if the cable in periods of the year is operated below rated voltage.

G. Reactive Power Compensation

Operation at variable voltage does not reduce the maximum amount of VAR compensation that need to be installed as long as the cable in periods are operated at rated voltage.

The analysis has tacitly assumed that the operation of the system is such that the reactive power produced by the cable can be absorbed at both ends. In practice, this implies that about 50% of the reactive power is consumed by the wind farm. This consumption can be achieved using conventional shunt reactors, or by means of controlling the wind turbines. It is emphasized that the shunt reactors do not need to be controlled when the cable operating voltage is adjusted since the cable VAR production and the reactor VAR compensation are both proportional to the square of the operating voltage.

The case study throughout this work assumed reactive compensation at both cable ends. The concept is also applicable to systems with reactive compensation along the cable route. An additional mid-point compensation will for the same cable distance reduce the reactive losses. The annual efficiency improvement that can be achieved by operating at variable voltage can therefore be expected to be somewhat lower for a system with mid-point compensation (for the same cable length). The combination of both methods will however have the potential to give higher annual efficiency than each method alone.

H. Operating Voltage for Maximum Power Transfer Capability.

In addition to improving cable efficiency, it is also possible to use voltage adaption for extending the maximum useful power transfer capability of a given cable. Using the system model described in Sections II and III together with the cable parameters in Table I, we analyze the maximum power transfer that can be achieved as function of the cable length and the cable operating voltage, without consideration to the cable efficiency. The maximum power transfer is calculated by searching for the wind farm voltage (magnitude factor α and phase angle β) which maximizes the transmitted power while respecting the current limit in the cable. The permissible voltage variations on the wind farms side are defined in Section III.

Fig. 20 shows with thin lines the maximum power transfer capability as function of the cable length, with the cable operating voltage as parameter (four alternative voltage levels). The solid lines denote the power supplied by the wind farm so that the difference between dashed and solid line represent the cable losses. The thick lines denote the envelope curves that result if one for each length operates at exactly the voltage that maximizes the transmission capacity. It is observed that by reducing the operating voltage it becomes possible to transmit power over longer distances. For instance, with 1.0 p.u. operating voltage the maximum useful cable length is shorter than 270 km. By reducing the operating voltage to 0.6 p.u., the same cable can be used for lengths up to 400 km, although with a reduction in both maximum permissible transmitted power and cable efficiency.

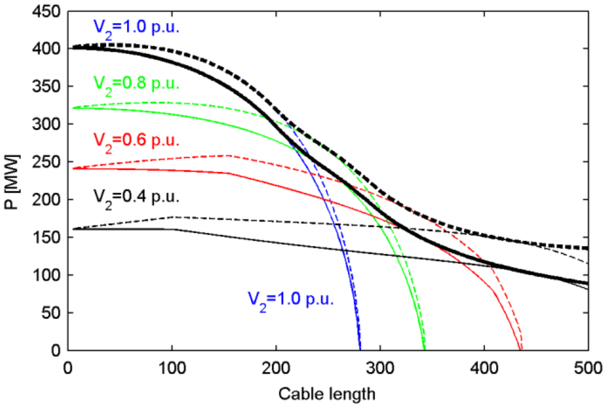

Fig. 20. Thin lines: maximum power transfer capability as function of cable length with (fixed) cable operating voltage (onshore side) as parameter. Dashed lines: produced power at wind farm; solid lines: power delivered to transformer on shore side. Thick lines: ditto result with use of optimal operating voltage. All curves are for the cable with parameters as in Table I.

I. Simplified Analysis

In this work, the exact PI-equivalent (5) has been used to represent the cable. Reference [10] describes a simplified approach for loss evaluation by assumption of zero voltage variation along the cable and 50% reactive compensation on each side. Fig. 21 shows that the simplified approach gives a fairly good agreement with the optimal result although the efficiency is underestimated, in particular for high power transfers where the efficiency is underestimated by nearly 1% which implies 15% overestimation of the losses by (18) (At the point of maximum transfer with 1.0 p.u. voltage (318 MW), the optimization gave α=1.06, β=7.7°).

It is important to note that the simplified analysis ignores the series voltage drop along the cable. If one tries to operate the real system with the same voltage magnitude on both cable ends (α=1) one will therefore experience a large reduction of the power transfer capability as was shown in Section V-D. Another limitation of the simplified method is that it will not be able to account for variable resistance along the cable due to temperature variation. The proposed method can easily handle that situation by cascading of exact PI-sections (Fig. 3) as mentioned in Section VIII-E.

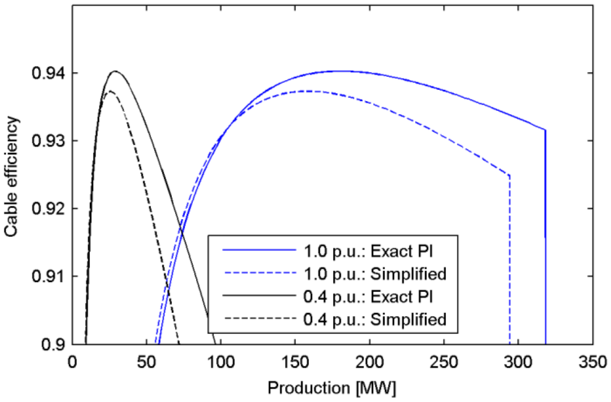

Fig. 21. Illustration of difference between use of simplified loss evaluation according to [10] and use of exact PI-equivalent.

IX. CONCLUSIONS

This study considers a wind farm HVAC transmission system where a cable connects a wind farm to the onshore grid via two transformers. The cable efficiency is analyzed using a detailed cable model based on distributed electrical parameters. From the analysis, the following conclusions are reached:

1. For a given cable length, the maximum attainable cable efficiency is independent of the cable operating voltage.
2. The operating voltage affects the power transmission level at which the maximum cable efficiency is attained. The maximum efficiency appears at lower power levels when operating voltage is reduced.
3. The cable efficiency can be increased if tap-changers are used to adjust the operating voltage according to the variations in the instantaneous wind power production levels. Calculations for a 200 km cable connecting a 320 MW wind farm showed that loss reduction of 9% is achievable by simply using a ±15% voltage regulation of the two transformers.
4. Usage of an even higher regulation leads to further improvements in the cable efficiency. If voltage can be varied between 0.4 and 1.0 p.u. one can achieve a loss reduction of 13% for the same wind farm.
5. The benefit of variable transmission voltage is highest for wind farms having a low utilization factor. A loss reduction of 21% was demonstrated for a 200 km/320 MW wind farm with low utilization factor when operated with variable voltage between 0.4 and 1.0 p.u.
6. Usage of a reduced operating voltage can also be used as a means of increasing the maximum transmission length for a given cable, although the permissible level of the transmitted power is reduced compared to short lengths.

The results presented here are relevant for those who are planning and engineering wind farms as well as for those optimizing cable designs for a given plant. The proposed methodology has the advantage that it can be realized without introducing new technology that needs to be developed or qualified.

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XI. BIOGRAPHIES

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