21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

B1-118

CIGRE 2018

Ampacity calculation method for deeply buried wind farm AC submarine export cables

D. VREE[1], S. VINK, J.W. VAN DOELAND
Energy Solutions B.V.
The Netherlands

F.S.W. DE VRIES
TenneT TSO B.V.
The Netherlands

SUMMARY

This paper presents a method to be used for dynamic ampacity calculations for deeply buried wind farm AC submarine export cables which is based on two load steps: a first preloading step reflecting the long-time average export cable load and a second full load step representing a period with maximum wind farm power output.

The method is intended to be used for tendering purposes where the client can define the ampacity requirements by specifying three additional parameters (next to the full load current and environmental conditions) which define the two load steps to be calculated by the tenderers. This simplified method brings advantages to both client and tenderers.

The parameter defining the preloading step ($\mathbf{I_{al}}$, representing the long-time average load of the windfarm) and the parameter defining the full load step ($\mathbf{t_{90}}$, the duration of the full-load current until conductor temperature reaches 90 °C) are derived using a series of cable current values over a three year period based on a wind data set and a fictitious production curve.

For determining $\mathbf{t_{90}}$ which defines the actual dynamic ampacity of the method, a dynamic temperature modelling tool was used to determine the highest conductor temperature $\boldsymbol{\theta_{c\text{-}max}}$. For 50 cases varying cable type, soil coverage and thermal resistivity of the soil, the results show that $\mathbf{t_{90}}$ can be related to $\boldsymbol{\theta_{c\text{-}max}}$ by determining for each case a time $\mathbf{t_{max}}$ which is the duration of the full-load current step until the conductor temperature reaches the same temperature $\boldsymbol{\theta_{c\text{-}max}}$ as was determined by the dynamic modelling tool. $\mathbf{t_{90}}$ can be related to $\mathbf{t_{max}}$ independently from soil and burial conditions where $\mathbf{t_{90}}$ should be larger than $\mathbf{t_{max}}$. The higher the margin between $\mathbf{t_{90}}$ and $\mathbf{t_{max}}$, the lower the risk profile that $\boldsymbol{\theta_c}$ actually will reach 90 °C.

By using the proposed dynamic ampacity method, an increase of ampacity of more than 20 % was found for the example used in this paper at the maximum assessed soil coverage of 10 m.

KEYWORDS

AC - Submarine - Export - Cable - Ampacity - Dynamic - Deeply buried - Offshore - Wind farm

[1] **D.Vree@Ensol.NL**

1 Introduction

For a (submarine) high voltage cable system connecting onshore or offshore windfarms, tendering is often based on functional requirements made by the client (tendering entity) where the design responsibility lies with the cable manufacturer (tenderer). During such a tender, different cable manufacturers (tenderers) must provide a cable design and therefore conduct ampacity calculations. To create a level playing field, the client must provide the conditions for the ampacity calculations including the calculation method and the environmental conditions (e.g. burial depth, thermal resistivity of the soil). For the definition of ampacity requirements the IEC standards [1] and [2] are commonly used.

A windfarm imposes a fluctuating load profile onto the cable system (arbitrary load patterns, see [3]) and the application of [1] for the ampacity calculations considering the maximum windfarm power output (at high wind speeds) will result in an over-dimensioned cable system [4, 5].

When considering a cable route with a soil coverage of 5 m or more (due to seabed mobility, deeply buried cables or deep horizontal directional drillings, HDD's), an additional factor will increase this effect of over-dimensioning as explained in [6]: a large time constant of the soil layer above the buried cable. With the large soil coverages combined with the fluctuating load profile of a windfarm, static ampacity calculations [1] lead to over-dimensioning of cables possibly resulting in an (unnecessarily) expensive cable section or even to a required conductor cross section not available in the market.

The main goal of the study presented in this paper was therefore to develop a method for ampacity calculations for fluctuating load of a wind farm based on [2] with limited complexity of the method such that it can be used in a public tender. This means that the method must be usable without providing long time wind data and a wind turbine power curve to the tenderers and with a similar risk profile as a traditional static ampacity calculation.

2 Methodology

The method is based on [2] where the formulas of section 2, clause 4 are used. In principal the loading of the temperature response of the cable will be modelled by two load steps as depicted in Figure 1.

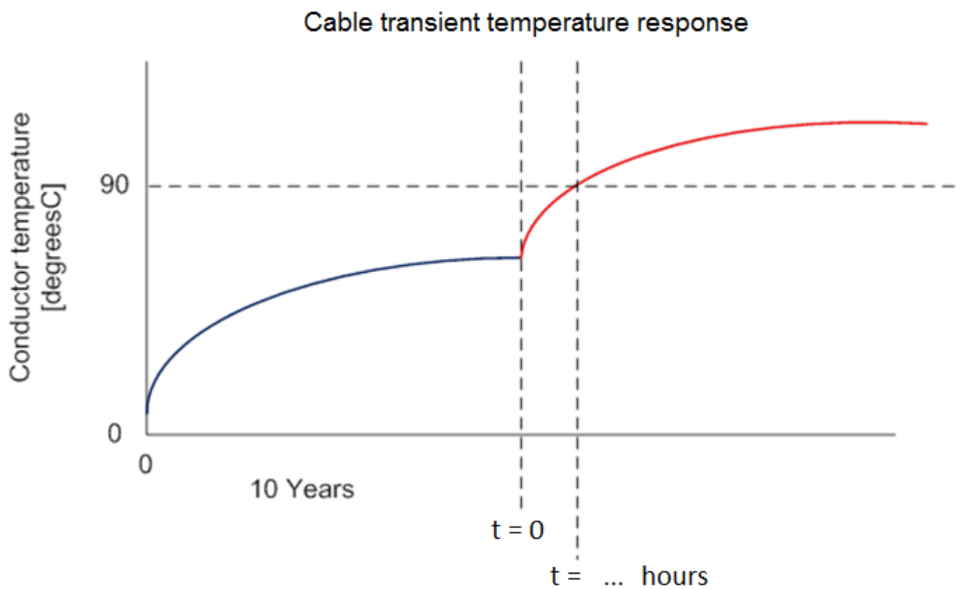

Figure 1. Cable transient temperature response based on two load steps

The first load step represents the average load of the windfarm and should be based on the applicable wind measurements, the foreseen wind turbine type and a long operational time (e.g. 10 years). A method to determine this average load will be presented in this paper below in chapter 3.

A second load step is then used where the full load condition is considered at maximum windfarm power output. With this step, the time ($\mathbf{t_{90}}$) is calculated until the conductor temperature reaches 90 °C under these full load conditions. This time ($\mathbf{t_{90}}$) defines the actual ampacity of the cable: the longer the time the higher the ampacity. By determining the minimum $\mathbf{t_{90}}$, the client is able to specify the ampacity only using this one parameter.

For example to reflect a risk profile similar to a static ampacity calculation according to [1], $\mathbf{t_{90}}$ shall be high enough, such that the risk that a conductor temperature of 90 °C is actually reached (and the windfarm output must be curtailed) is almost 0. A method to determine the minimum $\mathbf{t_{90}}$ is presented in this paper below in chapter 4.

Combined with the typical parameters to be specified by the client such as full load current (at maximum output of the windfarm), depth of burial (soil coverage) and thermal resistivity of the soil, the above three parameters will determine which cable type fulfils or does not fulfil the ampacity requirements. The parameters are summarized in Table 1. For the tender requirements, the client only needs to define these parameters for the tenderers to be able to determine the dynamic ampacity of their offered cable type(s).

Table 1: Parameters for method to determine dynamic ampacity

Parameter	Description
Basic parameters commonly used in ampacity calculations	
I_n [A]	Nominal (full-load) current at maximum power output of the windfarm
ρ [K.m/W]	Thermal resistivity of the soil
Soil coverage [m]	Layer of soil above the buried cable
Additional parameters to be used in dynamic ampacity calculation method	
I_{al} [A]	Current for preloading representing the long-time average load of the windfarm
t_{al} [h]	Duration of the preloading current
t_{90} [h]	Duration of the nominal (full-load) current until conductor temperature (θ_c) reaches 90 °C

Summarizing, the main advantages of this simplified method to determine the dynamic ampacity are as follows:

- the client does not need to provide large or confidential datasets to the tenderers (wind and/or wind turbine data) but only provides three additional parameters;
- the client is able to influence the risk profile on curtailment by varying only one parameter ($\mathbf{t_{90}}$);
- the tenderers are not required to perform complex calculations: their calculation efforts before contract award are limited.

3 Determination of the average load and time to be used for the preloading step

The average load $\mathbf{I_{al}}$ to be used in the first preloading step should reflect the long term average output current of the windfarm(s) to be connected and should therefore be derived from the wind farm load profile. In this study the preloading current $\mathbf{I_{al}}$ is derived from a) a fictitious wind turbine power curve and b) a 3 years wind data set from a North Sea measuring post [7].
This was the measuring pole 321 Europlatform (coordinates 10044; 447580). The location of this platform is presented in Figure 2. This site was in operation from 1983 up to 2006.

Figure 2: location of measuring pole 321 (source map: google earth)

The following actions were done to convert the raw wind speed data to actual currents to be used for the simulations:

From the raw data a selection was made over the period from 1-1-2001 until 3-6-2004, because this timespan had multiple periods with relative high wind speeds for a longer period of time. This wind speed data was converted from 29.1m height to a height of 100m (nacelle height turbines). This resulted in wind speeds from 0 m/s up to 32 m/s. In this period the wind speed was above 25 m/s for 64 hours in total.

A fictitious production curve of a turbine was taken to convert the wind speed into a resistive current on the export cable. The reactive charging current, depending on the location in the cable routing, was added to resistive current, thus creating the actual current in the cable (resistive + reactive[1]).
In Figure 3 the power curve and related export cable current are plotted against the windspeed.

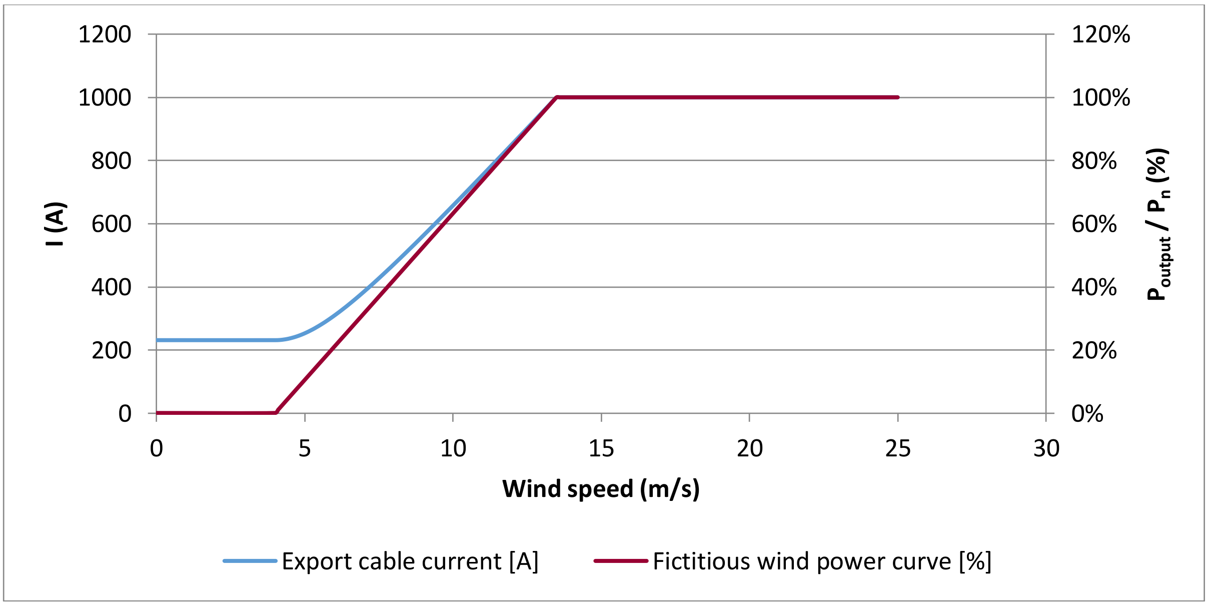

Figure 3: Power output and related export cable current plotted against the windspeed in [m/s]

[1] For the simulations the maximum reactive current at the end of a cable was used with a typical capacitance of C of 0,2 µF / km for a 1600mm2 conductor cross section and a length of 60 km. Reactive compensation of 50% at both ends of the cable connection was assumed.

The windspeed over the mentioned time period is then converted to currents using the orange curve of Figure 3. This resulted in a series of hourly varying currents over the complete time period (3 years and 5 month corresponding to 30.000 hours). The current $\mathbf{I_{al}}$ to be used in the simulations for the first preloading step is then determined by taking the root-mean-square (rms) of the currents over this complete time period. In this case, with a maximum current of 1000 A, the rms was calculated to be 670 A.

The time $\mathbf{t_{al}}$ of the preloading step used in this study is 10 years (3650 h). It is important that $\mathbf{t_{al}}$ is large enough such that the conductor temperature is stabilised after the preloading step has been completed (t = 0 in Figure 1).

4 Determination of time requirement before conductor temperature reaches 90 °C

4.1 Introduction

During the second load step, a full-load current ($\mathbf{I_n}$) is applied resulting in a further increase of the conductor temperature ($\boldsymbol{\theta_c}$) which will reach a $\boldsymbol{\theta_c}$ of 90 °C within a certain time $\mathbf{t_{90}}$. The minimum time before $\boldsymbol{\theta_c}$ may reach 90 °C determines the ampacity of the cable: the higher the minimum time is specified, the longer a cable can withstand the full load current which occurs at full wind farm power output.
The specified minimum time should therefore be related to the expected output current profile of the windfarm(s) and therefore, to the wind profile and wind turbine power curve.
A simple quantitative method would be to relate the time $\mathbf{t_{90}}$ to the longest period where the wind speed (and therefore output current) is above a certain threshold (e.g. > $\mathbf{I_{al}}$). Such a method however does not take into account the temperature effects when two or more of such periods are occurring close together possibly resulting in an underestimation of $\mathbf{t_{90}}$.

4.2 Dynamic temperature modelling with wind farm load profile

A more analytical method to determine $\mathbf{t_{90}}$, is by simulation of the conductor temperature in a dynamic temperature modelling tool based on [2]. A similar tool which has been used for dynamic rating is described in [8]. As input for the tool the series of currents are used as calculated from the actual wind data [7] and the wind turbine power curve as explained in chapter 3. To limit computational time, the modelling was performed on approximately one year of data (8600 hours) and this dataset is presented in Figure 4.

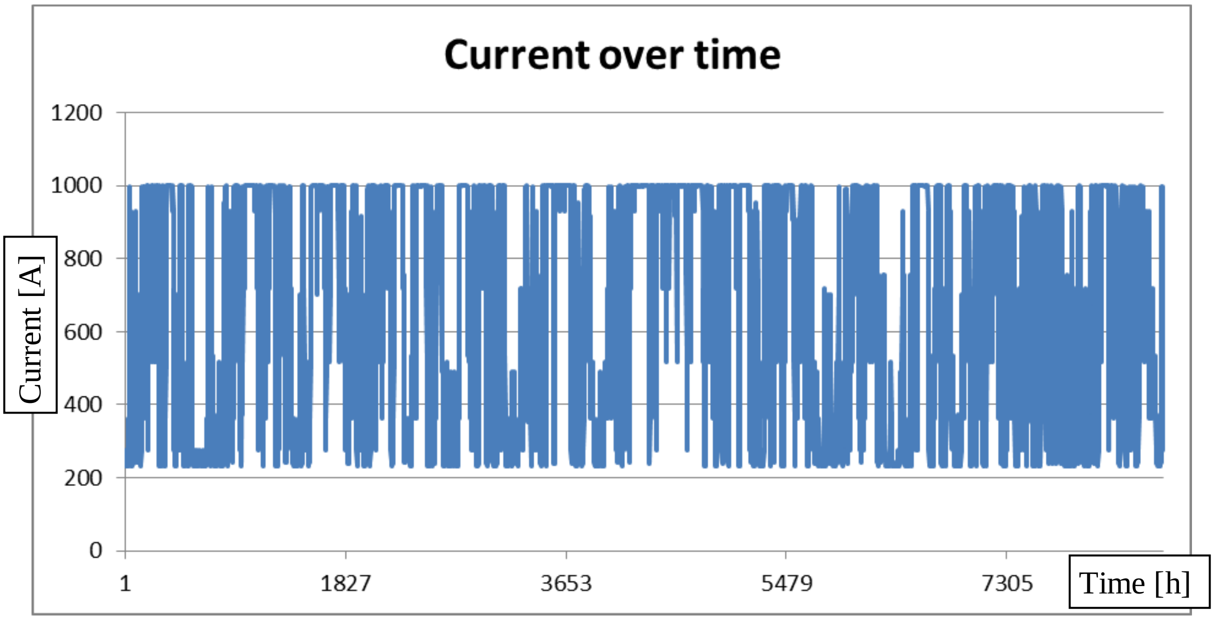

Figure 4: Hourly current series through the offshore windfarm export cable in [A] over one year

A resulting conductor temperature response for a 3-core 220 kV 1600 Cu cable type with soil coverage of 6 m and soil resistivity of 0,7 K.m/W is given in Figure 5.

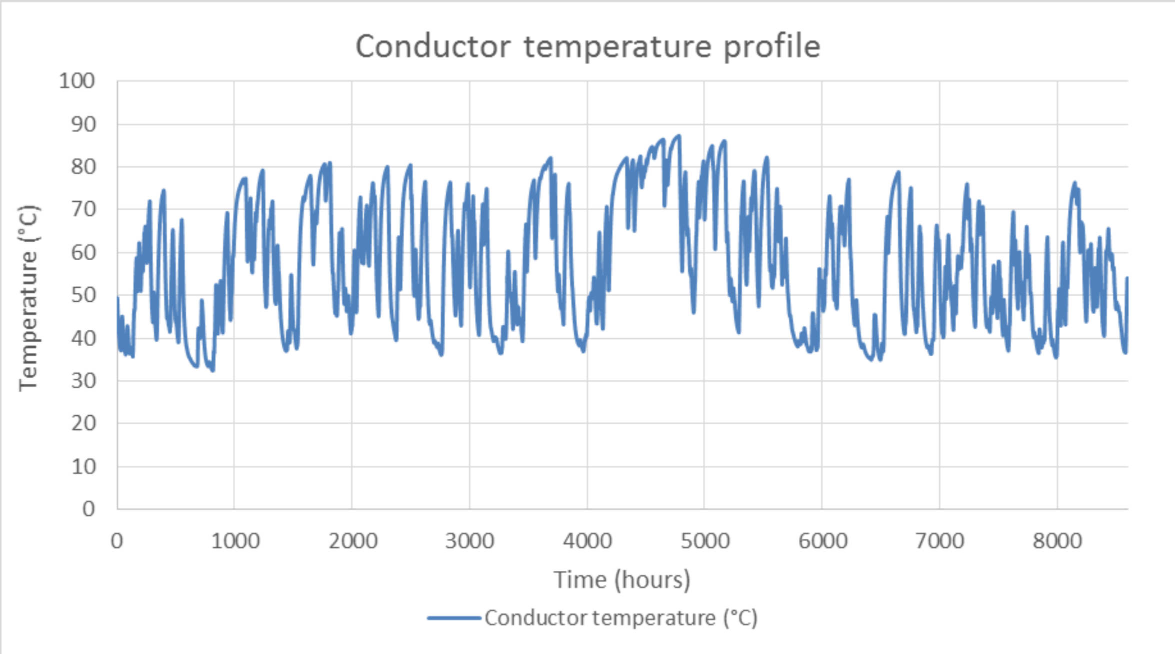

Figure 5. Example of the results of cable conductor temperature modelling of a wind farm load profile

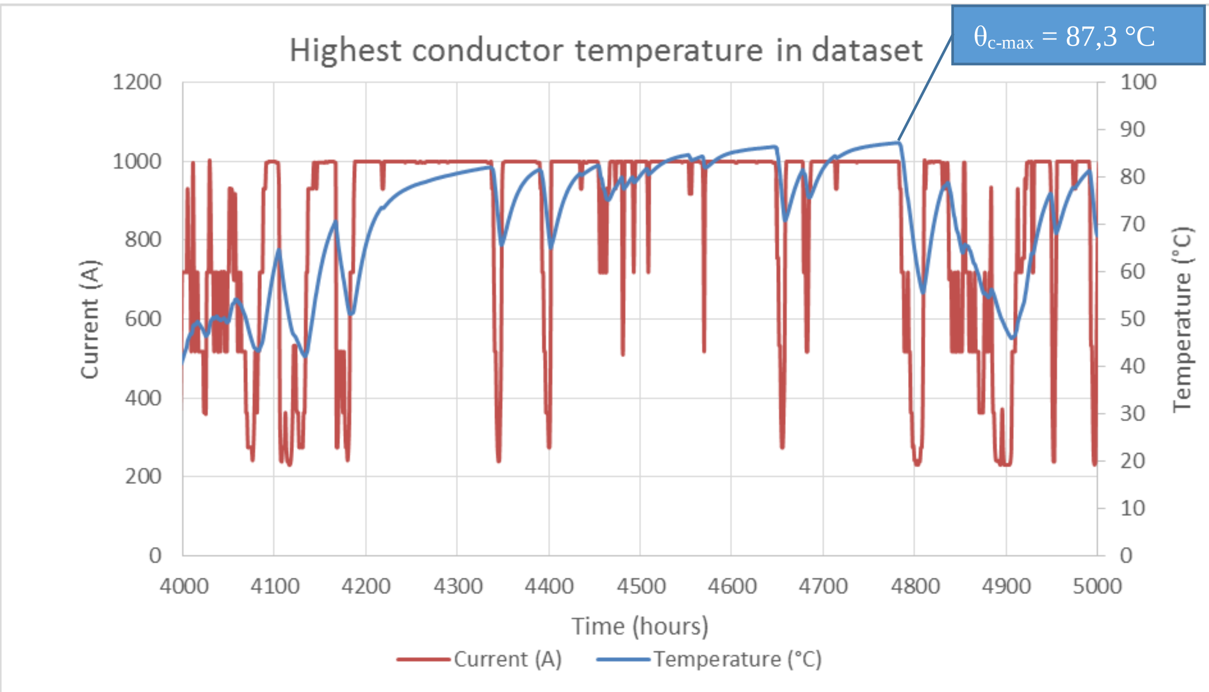

Figure 6: crop of Figure 5 of 1000 hours where at t = 4783 h a $\theta_{c\text{-}max}$ of 87,3 °C is reached

From the resulting temperature response, the maximum conductor temperature $\boldsymbol{\theta_{c\text{-}max}}$ can be determined as shown in Figure 6.

This maximum conductor temperature $\boldsymbol{\theta_{c\text{-}max}}$ has been determined for two cable types at various values of soil coverage and soil thermal resistivity. An overview of all cases which were assessed in this study is given in Table 2.

Table 2: Overview of 50 cases (2 x 5 x 5 = 50)

Cable types	Submarine 127/220 kV - 3x1600cu, Submarine 127/220 kV - 3x1600al
Thermal resistivity ρ [K.m/W]	0.5, 0.6, 0.7, 0.8, 0.9
Soil coverage [m]	2, 4, 5, 6, 10

Furthermore, an ambient temperature of 15 °C has been used.

A part of the results of the conductor temperature modelling are presented in Table 3 where $\boldsymbol{\theta_{c\text{-}max}}$ is shown for 10 of the 50 simulated cases. The maximum temperature occurred at the same time in all simulations around t = 4780 h. The temperature of the example in Figure 5 as determined in Figure 6 (87.3 °C), is shown in Table 3 at ρ = 0.7 K.m/W and soil coverage of 6 m.

Table 3: maximum conductor temperature $\boldsymbol{\theta_{c\text{-}max}}$ from simulations over one year of data

Cable type	Submarine 127/220 kV - 3x1600cu									
ρ [K.m/W]	0.6					0.7				
Soil coverage [m]	2	4	5	6	10	2	4	5	6	10
$\theta_{c\text{-}max}$ [°C]	71.1	76.2	77.6	78.8	81.6	78.0	84.1	85.9	87.3	90.6

4.3 *Determination of minimum t_{90} based on the dynamic modelling results*

Now we go back to the simplified dynamic calculation method. For the second step (using earlier determined values for $\mathbf{I_{al}}$ = 670 A, $\mathbf{t_{al}}$ = 10 years for the first preloading step and $\mathbf{I_n}$ = 1000 A), minimum $\mathbf{t_{90}}$ can be related to $\boldsymbol{\theta_{c\text{-}max}}$ for all above cases (Table 2). To do so, with the second step the time $\mathbf{t_{max}}$ has been calculated which is the time required for the conductor to reach $\boldsymbol{\theta_{c\text{-}max}}$ as was determined in the dynamic simulations (Table 3). This time $\mathbf{t_{max}}$ has also been calculated for all 50 cases varying cable type and the environmental conditions. The results of the same 10 cases are shown in Table 4 where $\mathbf{t_{max}}$ varies between 523 and 584 h. Although obviously $\boldsymbol{\theta_{c\text{-}max}}$ increases significantly when soil coverage and thermal resistivity increase (Table 3), the variance of $\mathbf{t_{max}}$ is limited and stabalized for soil coverage between 5 m and 10 m over all assessed soil thermal resistivity values (0.5 to 0.9 K.m/W). This is applicable to both cable types which are assessed in this study. It is therefore concluded that the minimum time $\mathbf{t_{90}}$ can be related to $\mathbf{t_{max}}$ independently from soil and burial conditions where following should be observed:

- Only one value for $\mathbf{t_{90}}$ may be specified for all environmental conditions along the cable route;
- $\mathbf{t_{90}} > \mathbf{t_{max}}$;
- The higher the margin between $\mathbf{t_{90}}$ and $\mathbf{t_{max}}$, the lower the risk profile that $\boldsymbol{\theta_c}$ actually will reach 90 °C.

Table 4: $\mathbf{t_{max}}$ and $\boldsymbol{\theta_c}$ for 10 cases

Cable type	Submarine 127/220 kV - 3x1600cu									
ρ [K.m/W]	0.6					0.7				
Soil coverage [m]	2	4	5	6	10	2	4	5	6	10
t_{max} [h] to reach $\theta_{c\text{-}max}$	523	579	582	582	584	521	576	583	582	584
t_{90} [h]	n/a	n/a	n/a	7802	3797	n/a	1785	1269	972	519
θ_c [°C] at 600 h	71.6	76.3	77.8	78.9	81.7	78.7	84.3	86.1	87.5	90.8
θ_c [°C] continuous[2]	77.2	86.6	89.7	92.3	99.4	85.6	96.2	99.9	102.9	111.4
Ratio (%) between θ_c at 600 h & continuous	8%	13%	15%	17%	22%	9%	14%	16%	18%	23%

[2] As calculated using [1]

A summary of the process to determine $\mathbf{t_{90}}$ can be found in Figure 7.

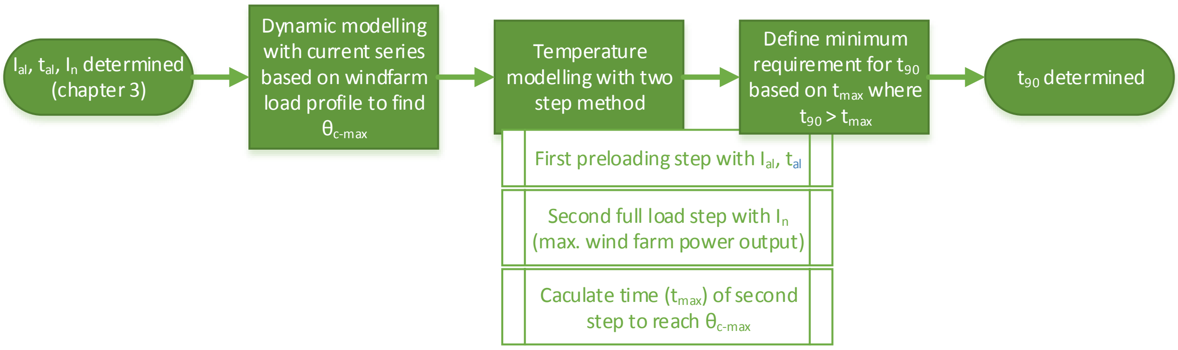

Figure 7: process to determine $\mathbf{t_{90}}$

Table 4 shows also the actual $\mathbf{t_{90}}$ per case and an assessment on $\boldsymbol{\theta_c}$ when the minimum of $\mathbf{t_{90}}$ would be specified at 600 h which could be chosen as the minimum ampacity requirement for this example. Also the conductor temperature for continuous ampacity as calculated using [1] is provided. As can be seen from the colours used in the table, a requirement for $\mathbf{t_{90}}$ > 600 h would be fulfilled in nine of the 10 cases shown. A continuous ampacity requirement based on [1] would only be fulfilled in four of the 10 cases. At the highest soil coverage assessed in this study (10 m) the ratio between $\boldsymbol{\theta_c}$ at 600 h & $\boldsymbol{\theta_c}$ for the continuous current is more than 20%.
Should the minimum requirement for $\mathbf{t_{90}}$ be increased to lower the risk that $\boldsymbol{\theta_c}$ actually will reach 90 °C, the ratio compared to continuous ampacity is decreased for the same cable type. The selection of the minimum requirement for $\mathbf{t_{90}}$ is therefore a trade-off between costs (for the cable) and risk (on curtailment).

In order to further validate the process as summarized in Figure 7, a second current series has been selected from the 3,5 years data set to repeat the process for five of the assessed cases as a sensitivity check. Results are shown in Table 5. The results show again the relation between $\boldsymbol{\theta_{c\text{-}max}}$ and $\mathbf{t_{max}}$ independently from the soil coverage which is varied over the five cases. This current series includes less periods with high wind speeds resulting in a lower $\boldsymbol{\theta_{c\text{-}max}}$ and therefore also lower $\mathbf{t_{max}}$. This example shows that the used wind data has a great impact on the found results and care should be taken when selecting wind data to be used for dynamic ampacity calculations.

Table 5: validation (sensitivity check) of $\boldsymbol{\theta_{c\text{-}max}}$ and $\mathbf{t_{max}}$

Cable type	Submarine 127/220 kV - 3x1600cu				
G [K.m/W]	0.6				
Soil coverage [m]	2	4	5	6	10
$\theta_{c\text{-}max}$ [°C]	69,2	73,8	75,1	76,2	79,0
t_{max} [h] to reach $\theta_{c\text{-}max}$	321	325	318	316	315

5 Conclusions

In this paper a method is presented to be used for dynamic ampacity calculations for deeply buried wind farm AC submarine export cables which is based on two load steps: a first preloading step reflecting the long-time average export cable load and a second full load step representing a period with maximum wind farm power output.

The method is intended to be used for tendering purposes where the client can define the ampacity requirements by specifying three additional parameters (next to the full load current and environmental conditions) which define the two load steps to be calculated by the tenderers.

The main advantages of this simplified method to determine the dynamic ampacity are:

- the client does not need to provide large or confidential datasets to the tenderers (wind and/or wind turbine data) but only provides three additional parameters;
- the client is able to influence the risk profile on curtailment by varying only one parameter ($\mathbf{t_{90}}$);
- the tenderers are not required to perform complex calculations: their calculation efforts before contract award are limited.

The parameter defining the preloading step ($\mathbf{I_{al}}$, representing the long-time average load of the windfarm) and the parameter defining the full load step ($\mathbf{t_{90}}$, the duration of the full-load current until conductor temperature reaches 90 °C) were derived using a series of cable current values over a three year period based on a wind data set and a fictitious production curve. Figure 7 depicts the process of determining $\mathbf{t_{90}}$.

Following conclusions on the presented two step dynamic ampacity method can be given:

- the variance of $\mathbf{t_{max}}$ is limited and stabalized for soil coverage between 5 m and 10 m over all assessed soil thermal resistivity values (0.5 to 0.9 K.m/W). The minimum time $\mathbf{t_{90}}$ can therefore be related to $\mathbf{t_{max}}$ independently from soil and burial conditions.
- One value for $\mathbf{t_{90}}$ may be specified for all environmental conditions along the cable route in a tender where $\mathbf{t_{90}} > \mathbf{t_{max}}$.
- The difference in ampacity between using the proposed method compared to continuous ampacity increases if soil coverage increases. For a soil coverage of 10 m the ratio between $\boldsymbol{\theta_c}$ at 600 h and $\boldsymbol{\theta_c}$ for the continuous current is more than 20%.
- For the wind farm data as used in this study, the minimum time $\mathbf{t_{90}}$ (before the conductor temperature $\boldsymbol{\theta_c}$ may reach 90 °C) shall be at least 600 hours. This time may be increased to reduce the risk that $\boldsymbol{\theta_c}$ actually will reach 90 °C and that the wind farm must be curtailed.
- However, by increasing the minimum $\mathbf{t_{90}}$ the ratio between $\boldsymbol{\theta_c}$ at the minimum $\mathbf{t_{90}}$ and $\boldsymbol{\theta_c}$ for the continuous current decreases.

Not assessed in this paper and therefore recommended for further study are the following items:

- Analysis of the impact of increasing $\mathbf{t_{90}}$ on the balance between cable costs and risk on wind farm curtailment;
- Assessment of the impact on varying the preloading time $\mathbf{t_{al}}$;
- In general to validate dynamic ampacity calculations with temperature measurements of export cables of operational wind farms.

BIBLIOGRAPHY

[1] IEC Standard 60287 "Calculation of the Continuous Current Rating of Cables (100% load factor)" (First edition 1969, Second edition 1982, Third edition 1994-1995)

[2] IEC Standard 60853-2 "Calculation of the Cyclic and Emergency Current Ratings of Cables. Part 2: Cyclic Rating Factor of Cables greater than 18/30 (36) kV and Emergency Ratings for Cables of All Voltages" (First edition 1989, Amendment 2008)

[3] CIGRÉ “A Guide for Rating Calculations of Insulated Cables” (Technical Brochure 640, 2015)

[4] CIGRÉ “IMPLEMENTATION OF LONG AC HV AND EHV CABLE SYSTEMS” (Technical Brochure 680, 2017)

[5] J. Pilgrim, S. Catmull, R. Chippendale, R. Tyreman & P. Lewin “Offshore Wind Farm export cable current rating optimisation” (Offshore 2013, Germany. 2013)

[6] Dorison E., Anders, G. and Lesur F., “Ampacity calculations for deeply installed cables”. (IEEE Trans. on Power Delivery, Vol. 25, No. 2, pp. 524-533, 2010)

[7] KNMI measuring pole 321 Europlatform, coordinates 10044; 447580, ROYAL NETHERLANDS METEOROLOGICAL INSTITUTE, (Reports: http://www.knmi.nl/samenw/hydra)

[8] Colla, L. and Marelli, M. “Dynamic rating of submarine cables – Application to offshore windfarms”, (EWEA Offshore, Frankfurt, Germany 2013)