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***Abstract*— This paper provides a tutorial overview of dynamic thermal rating concepts and methods applied to electric cables. Although most analytical developments and models have been proposed many years ago and are covered by IEC Standards, numerous recent developments suggest refinements to these models and enhanced applications. In particular, on the modelling side, the latest contributions refer to analytic models, variants of the equivalent circuit of the soil to be used in finite difference methods, applications of 2D and 3D finite element methods, and definitions of simplified models and equations validated with respect to the results obtained from FEM simulations and experimental measurements. On the methodological side, the overview also covers optimal cable sizing, reliability aspects, risk estimation, and forecasting of dynamic cable rating.**

***Index Terms*—Electric cables, Thermal model, Dynamic line rating, Cable rating, Reliability, Monitoring, Review.**

I. Introduction

With the increase of the demand for electricity, the current flowing in the electrical lines (overhead lines and underground cables) is growing. The electrical lines are then subject to increasingly high thermal stress, reaching temperature peaks during the period of operation that can approach the thermal limits of the lines. The classical steady-state thermal rating is no longer considered to be sufficient to determine the limits of usage of the lines. On the one hand, the application of the steady-state thermal rating as the limit that must not be exceeded in any operating condition could be excessively conservative. In fact, the line could have a temperature evolution in time that leads to only a few relatively high temperature values. In this case, slightly exceeding the steady-state limit for a short period of time would not affect too much the lifetime of the materials (e.g., the cable insulation). On the other hand, reaching excessive temperatures could lead to abnormal conditions, such as hot spots that could appear in some points of the lines. Hence, during the years the assessment of the thermal stress of the lines has passed from the steady-state thermal rating to a more general Dynamic Line Rating (DLR) or Dynamic Thermal Rating (DTR), able to better characterize the thermal transients and their consequences.

Most of the literature on DLR is dedicated to overhead lines [1]. However, especially in recent years, growing attention has been dedicated to the operation of underground cables, considering the so-called Dynamic Cable Rating (DCR). The study of the thermal behaviour of the underground cables is essential for cable design and manufacturing, as well as for determining the possible occurrence of anomalous conditions that create hot spots and could lead to cable failures. The effects of cable failures on the reliability of the electrical systems have also to be assessed, especially, when joints are added during the cable repair. A relevant aspect is the sensitivity of the current limits of the cables to the changes of the thermal conditions (and of the corresponding parameters of the thermal model of the cable and the soil) during the time. For increasing the effectiveness of the definition of the cable rating in practical applications, it is crucial to address risk estimation and DCR forecasting.

The main contributions of this paper are to provide a synthetic overview of some aspects referring to the determination of the DCR and its impact on the power system operation. Section II addresses the modelling of cable and soil, focusing on the thermal phenomena relevant to the assessment of cable heating, the DCR impact on distribution system reliability, and some notes on cable monitoring aspects. Section III deals with solution methods for DCR. The Conclusions section contains the final remarks.

II. Cable and Soil Modelling

A. Thermal aspects

The thermal calculations used for cable design are based on the physical properties of the materials, the cable loading, and the heat transfer properties of the surrounding ambient, (e.g., the soil). A number of exogenous aspects are also important to assess cable heating. These aspects include variable thermal resistivity of the earth, mutual thermal effects of multiple cables, as well as faults in cables, terminals and junctions. The lack of uniformity of the cable structure and the external conditions can lead to the formation of hot spots, which cause premature ageing and failures. Since the soil resistivity and the cable loading change in time, the hot spot location can be variable in time.

The thermal model takes into account the ohmic losses and insulation losses. The latter is important because as far as there is no good heat transfer between cable and soil, the heat generated inside the cable (due to Joule, dielectric and

ferromagnetic losses) that does not flow outside causes the internal temperature growth and leads to insulation damage [2].

B. *Thermal modelling of the cable*

The typical thermal models of the cables have been constructed by resorting to the electro-thermal analogy [3-6] (Table I).

TABLE I. ELECTRO-THERMAL ANALOGY.

Thermal quantity	Units	Electrical quantity	Units
Temperature T	K	Electric potential V	V
Absolute zero	0 K	Ground potential	0 V
Heat Flow Rate $\dot{Q}$	W	Electric current I	A
Thermal conductivity k	W / (m·K)	Electric conductivity γ	1 / (Ω·m)
Thermal capacity C_t	J / K	Capacitance C_e	F
Thermal resistance R_t	K / W	Resistance R_e	Ω

Detailed representations of the equivalent circuit considered to model the cable in operational conditions have been presented for the internal part of the system (the cable) and the external part (the soil and the ambient). A single core of the cable can be represented considering cylindrical symmetry with isothermal coaxial cylindrical layers (Fig. 1). The equivalent circuit is formed by introducing a set of interconnected resistors, capacitors and generators. In particular, the resistors represent the thermal resistances, the capacitors represent the thermal capacities, and are essential to model the thermal transients in real operating conditions. The generators account for heat sources due to different types of losses (e.g., Joule losses in the conductor, dielectric losses, and losses in the sheath and armour) [7,8]. Between two layers, the resistors and capacitors can be connected in the equivalent circuit in a way consistent with "T" or "Π" circuit models with lumped parameters. After the connection of resistors and capacitors, any series resistances can be summed up together, and any parallel capacitances can be summed up together, to reduce the number of elements in the circuit.

Fig. 1 shows a conceptual scheme in which all the "T" circuit models are represented. However, depending on the material and size of the components, some resistances could be neglected (e.g. for shield and sheath).

Concerning the calculation of the parameters, the Joule and dielectric losses are generally calculated as suggested in the Standard IEC 60287 [9]. The thermal resistances and the thermal capacitances can be estimated with reasonable accuracy. The dependence of the cable conductor resistance on temperature is addressed in [10], by using the thermal circuit model. Some estimates of the cable parameters have been done without introducing the heat transfer equations and without considering a thermodynamic approach. In [11], the estimation of the resistance of Medium Voltage overhead lines and underground cables is made by using synchrophasor data provided by phasor measurement units (PMUs). The thermal circuit dynamics can then be represented as a system of ordinary differential equations [12,13].

In general, the thermal models of the single cables are combined by considering the mutual position of the cores, the possible further jacketing into multi-core cables, and the location of the cables in the ducts.

C. *Soil thermal model*

The main factor that characterizes the soil is its thermal resistivity. Considering a uniform soil, the standard IEC 60287 [9] based on [14] indicates how to calculate the soil thermal resistance and the effective soil thermal resistivity.

Thermal stability is the ability of the soil to maintain its thermal resistivity in the presence of a heat source [15]. The thermal resistivity of the soil changes depending on the moisture content. The major issue is that the heat that flows from the cable into the soil may lead to significant moisture migration away from the cable [16]. In this case, a dry zone with reduced thermal conductivity (thus higher thermal resistivity) could appear around the cable. This dry zone may also result in a temperature growth in the cable sheath, with further damage of the cable insulation and possible creation of hot spots. Classical solutions used to avoid the drying of the soil close to the cable are based on water cooling. A recent solution suggested in [17] is to use hydronic asphalt pavements. Another recently proposed solution to reduce the hot spots is gravitational water cooling [18], which can be applied when water cooling cannot be used. For particular types of cables, for example, self-contained fluid-filled (SCFF) cables, the presence of the parallel pipe water cooling requires to modify the thermal circuit [19]. In a

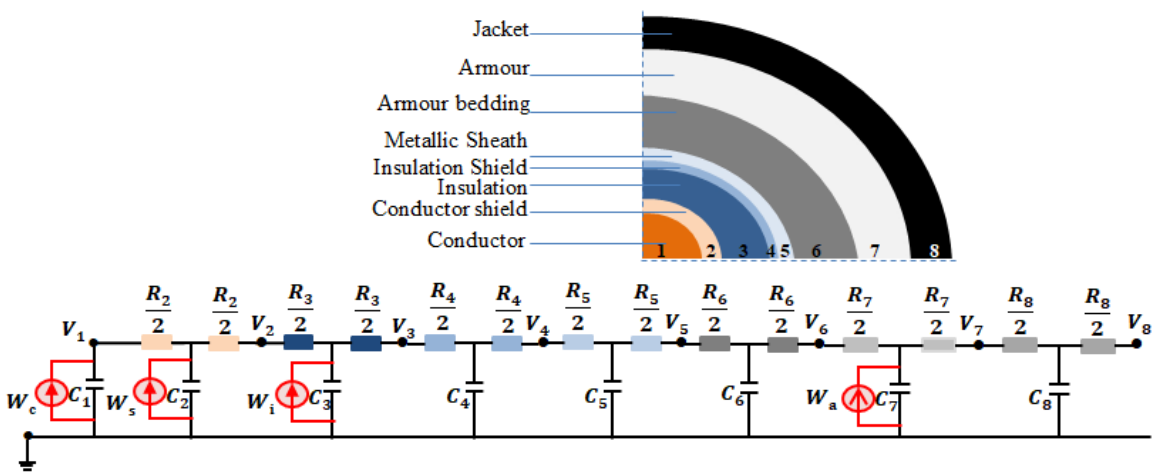

Fig. 1. Equivalent electrical model from electro-thermal analogy for a single-core cable, considering the representation of the parameters with the "T" model.

water-cooled cable, the soil thermal conductivity cannot be assumed as a constant. The water transport effect that occurs when the cable losses increase the temperature has to be considered [20].

D. Calculation of the current rating

When the soil thermal resistivity is known, the IEC Standard 60287 [9] provides the way to determine the current rating without exceeding the maximum allowable temperature, applying the Neher–McGrath method [14]. Generalized techniques have been introduced in [21] to account for the soil thermal instability in the calculations based on [14]. The reference [22] has addressed the particular issue of imposing the temperature limits at points different from the cable conductor. The reasons for these kinds of limitations are mainly environmental, and the temperature limit is applied to the external surface of the cable, or a given point in the surrounding ambient. This further limit imposes an additional constraint to the cable sizing, which has to be also considered in dynamic conditions.

In the calculations of the current rating, it is also crucial to consider the uncertainty of the parameters. Uncertainties mainly appear in the thermophysical properties of the soil and the evolution in time of the electrical load, which affects, in particular, the Joule losses of the cable [23]. Transient tolerance analysis of cable rating, carried out with interval mathematic, has been presented in [24]. A review on possible means to increase cable rating is provided in [7].

E. Solution methods

The thermal characteristics of the cables buried in the soil are typically studied with different techniques:

1) *Analytic models*
2) *Finite difference methods*
3) *Finite element methods*
4) *Simplified models and equations*

The *analytic models* are based on the solution of the diffusion equation that provides the transient temperature at any point of the soil. The classical model provides the solution in an exponential integral form [3,22,25]. Another analytical model presented in [26] assesses the cable rating considering the non-uniform underground temperature distribution calculated from heat transfer equations with boundary conditions.

The *finite difference* methods are based on the lumped parameter model constructed by using the electro-thermal analogy. These methods cannot easily represent the discontinuities in the material properties at the boundaries of the different cable layers.

The *finite element* method (FEM) integrates the governing equations of the thermal phenomena in a multi-physics environment, using the computational capabilities of the solvers [4]. A number of connected nodes represent the system, and the creation of the non-regular mesh is a crucial issue for the improvement of the computation time and the success of the detailed representation of the results. In steady-state, the FEM minimizes a given functional subject to a set of boundary constraints [27]. Some tools used for two-dimensional (2D) analysis are FEMM [28], FLUX [29] and ANSYS [30][31]. A FEM tool developed by the authors of [32] has been used with temperature-dependent thermal conductivity of a multi-layered soil in 2D. The numerical model contains non-linear functions of temperature, which are solved with a Newton-Raphson approach. The results from three-dimensional (3D) analysis have been reported more recently from FLUX 3D [33] with considerably long computation time even for short cables, and COMSOL with 2D model [34] and 3D model of Low Voltage cables [35]. The main limit of the FEM is the high computational burden needed to obtain detailed results from the 3D analysis. Another limit of the FEM is that it cannot provide a relation between the cable temperature and the parameters of the thermal circuit [2].

The *simplified models and equations* are used to represent the basic nature of the phenomena that lead to temperature variations. Even though the computational power available today enables the solution of highly meshed systems from FEM, the use of these simplified models has provided reasonable results in many cases. An example is reported in [36], where an equivalent circuit to represent the soil is introduced by adopting a non-uniform discretization of the soil into multiple layers for calculating the thermal transients. The conclusion is that five layers are suitable to obtain results very close to FEM results. Likewise, in [37] non-concentric models of the soil layers are used. Corrective coefficients are applied in [30] to the soil thermal resistance determined according to the Standard IEC 60287 [9], with validation obtained in comparison with 2D FEM results. The 3D multi-conductor cell analysis presented in [38] has shown a drastic reduction in the computation time to 3D FEM for a three-core armoured cable with helically wound wires. A 3D model of cables and joints is presented in [20], with satisfactory results with respect to measured values.

F. Reliability aspects

For reliability analysis, the cables are considered as repairable components. Cables are repaired by making joints. The process of cable repair has duration of some hours. However, the repair time is very low with respect to the timing considered for reliability analysis (e.g., mean time between failures), being the failures relatively rare events in the cable lifetime [39].

The models to determine the cable ageing and lifetime are affected by hot spot location and joints. Using a constant failure rate is not sufficient. The joints become a weak point of the cable, both for thermal reasons for the introduction of local resistances in the junction points and for mechanical reasons, since the cables are moved during the repair that follows the successive failures. In [40] the reliability calculations take into account the service restoration, using a probability distribution associated with the number of joints. The increase of the failure rate during the time or after repair events is discussed in [41] by introducing variable curves for reliability analysis considering ageing.

In [42] a data-driven approach is used to forecast the remaining life of cables, by predicting the time at which the cumulative effect of the features chosen to represent the possible problems exceeds a given threshold. In [43] indicators of cable ageing are defined by making a distinction between normal and emergency conditions, to point out the increased risk of failures during emergency periods. During emergencies, the cables can be used with a higher rating in short periods, assessing the risk to deteriorate the cable due to its thermal behaviour [44].

G. Cable monitoring

For DCR, the main variable of interest is the temperature. Thermocouples can be installed at various points of the

cable. However, the local installation of the thermocouples could be far from the actual hot spots, thus failing to identify the critical conditions along the cable length.

Distributed temperature sensing (DTS) [45] is used to get the temperature profile along the cable in real-time by placing optical fibre sensors inside the cable structure. The temperature profiles are created by analysing the Raman backscatter light in the optical fibre. The temperature can be used inside SCADA systems that monitor the operation of different cables in a network, providing information useful for both load monitoring and location of the most critical points along the cable. Some challenges for DTS applications are reported in [6]. In particular, the introduction of the optical fibre in the power cable jacket increases the cost of the cable, especially when there is the need of jointing the cable (also increasing the time to complete the cable jointing).

Furthermore, in this case, the optical fibre has a helical structure, and its length is higher than the cable length. An alternative is to locate the optical fibre externally to the cable. Still, in this case, the monitoring becomes far from the conductor, while it could be more suitable to measure the soil temperature. In the case of junctions, with an external optical fibre, the repair process becomes easier, but the identification of the temperature of the junction becomes less accurate.

The temperature monitoring can be more effective if a reference temperature monitoring is carried out when no current flows in the cable. In this way, possible temperature changes along the cable path can be identified and taken into account in the assessment of the temperature data when the cable is under operation.

DTS is used for extremely high voltage (EHV) cables. In the example presented in [19], a 52 kV AC submarine cable has been monitored. Further information on existing practices to set up a real-time temperature rating, including distributed temperature sensing and the presence of a suitable SCADA system, are presented in [46].

III. Solution Methods for DCR

In the next subsections, some DCR solution methods will be described, namely the optimal sizing of the export cable of offshore wind farms, the probabilistic risk estimation and, finally, the forecasting methods of DCR.

A. Optimal sizing of cables

The optimal sizing of cables is usually performed by assuming a static cable rating (SCR), as recommended by the IEC technical Standards IEC60287 [9]. When the SCR is considered, the current-carrying capacity (or ampacity) of the cable is calculated as the continuous current carried by the cable, such as the continuous conductor temperature will be equal to the maximum allowable conductor temperature (e.g., for most of the cables this value is 90°C). In this approach, steady-state conditions are assumed for the useful life of the cable. The Standard IEC 60287 [9] describes how to calculate cable rating with a constant load, taking into account all loss terms in the cable (ohmic losses, dielectric losses, armour, screen and sheath losses, etc.). The simplified thermal model of the cable and its environment is based on Neher/McGrath's equations [14], as already mentioned in Section II.D. The choice of the adequate cable section is made by comparing the cable operating current with the ampacity values. The calculations can be performed easily for simple configurations.

In some particular conditions, these sizing methods can lead to under-utilized components because of the high variability of currents. As such, the static rating results in a conservative value that underestimates the capacity of the cable because the worst case is assumed. A case is represented by export cables connecting wind farms, that are characterized by “low capacity factors and high power production variability” [47].

If different sizing methods are applied, it is likely that a smaller nominal value can be chosen given certain conditions. A maximum current rating increase can be achieved as well as a reduction in terms of cable cross-section is obtained if compared with the traditional thermal design based on steady-state current [48].

To catch the characteristics of cable current in these conditions, the sizing of offshore export cables can follow the procedure delineated by the IEC standards IEC60853-1 [49] and IEC60853-2 [50] addressing the cyclic ratings for cables. These standards consider the case of the cyclic rating of a single cable or groups of equally loaded identical cables and propose a cyclic rating factor that has to be multiplied by the permissible peak value of current during a daily cycle. The aim is, also in this case, not to exceed the maximum allowable temperature. The cyclic rating factor depends on the characteristics of the daily cycle and does not depend on the magnitudes of the currents [49,50].

In [51], a procedure based on IEC60853-2 [50] is proposed for the rating of the export cable of offshore wind farms. In particular, an equivalent cyclic load profile is derived by assuming a wind speed time series.

A new approach [52] takes into consideration a dynamic load cycle profile, consisting in worst case equivalent step-wise load profiles.

An iterative dynamic cable rating method is proposed in [53] for the export cable of offshore wind farms; three-core XLPE submarine cables are taken into consideration. The iterative method is based on a thermal cable analysis, according to IEC 60853-2 [50]. Since a dynamical response of the cable is needed, the authors consider a thermal ladder network and, on the basis of this network, the transient temperature response by a step function is obtained. The iterative dynamic cable rating procedure includes a first choice of the cable; then the cable loading, as well as the parameters of the thermal ladder network, are calculated. The conductor temperature is, finally, evaluated and compared with the maximum allowable temperature. When a cable not exceeding the maximum allowable temperature is found, the iterative procedure is stopped.

A review of the methods applied for sizing cable connecting offshore wind farms, including the ones based on DCR, can be found in [47].

B. Probabilistic risk estimation

Export cables for offshore wind farms are considered in [54], where a probabilistic methodology for temperature risk assessment is proposed. This study aims to estimate the cable temperature exceedance with respect the allowable maximum temperature 6h, 12h and 24h ahead to maximize the power that the cable will export from the offshore wind farm to the landfall. A decision tool is established, allowing the decision maker to reduce or avoid wind power curtailment based on the calculated risk index.

The probabilistic methodology proposed in [54] first estimates the current that the export cable will carry in the hours ahead: 3 time-steps are considered, namely 6h, 12h or

24h. Scenarios of cable currents are determined based on historical data of wind speed from an offshore wind farm location and of the power curve the wind turbine (the power curve allows to calculate the generated wind power for each value of wind speed). Then, a finite difference analysis of the cable is performed to calculate the conductor temperature. Finally, the risk of exceeding the maximum allowable temperature is estimated.

C. DCR forecasting methods

DCR methods are formulated considering time-varying environmental and circuit conditions. A dynamic rating can, thus, be determined by meeting the constraint related to the maximum allowable temperature. The procedure aimed at evaluating the DCR needs a number of input variables, including the ones that define the thermal conditions of the surrounding ambient; if the cable is buried, the temperature conductor also depends on the soil conditions. In particular, further, than the ambient temperature, the soil conditions depend on precipitations and degree of saturation. For operational problems, the DCR can be performed with different objectives that lead to different time horizons (ranging from intraday to day-ahead time scales).

The problem of intraday and day-ahead forecasting of the DCR is addressed in [55]. In this paper, accurate modelling of the cable-soil thermal-hydraulic dynamics is applied. In fact, the soil dynamic characteristics (i.e., soil temperature at the burial depth, soil thermal resistivity, and soil thermal diffusivity) affect the thermal exchange between the cable and the surrounding and, them, affect the conductor temperature. In [55], two methods aimed at forecasting the DCR are proposed: i) a physical-statistical method for at intraday time scale; ii) a data-driven method adapted for intraday and day-ahead time scales. The first method uses Support Vector Regression (SVR) based forecasts of soil temperature at the upper layer, precipitation, and cable current throughout the whole forecast lead time. Then, using the forecasts of the environmental conditions, a thermal-hydraulic model of the soil is solved to estimate the soil dynamic characteristics over the forecast lead time. The DCR is forecasted at the target hour, by applying the IEC cable-soil thermal model, with the constraint that the conductor temperature will not exceed the maximum allowable temperature. In particular, the transient thermal model is applied. The second method uses historical measurements and historical weather forecasts of precipitation and soil temperature at the upper layer, to estimate dynamic soil characteristics by means of the thermal-hydraulic model of the soil during the entire available history. Then, the historical DCR is estimated by applying the thermal model of the cable and soil in transient conditions. Finally, the forecasting of the DCR at the target hour is performed by using a regression model on historical DCR values.

IV. Conclusions

This paper has addressed some aspects linked to the determination of the dynamic cable rating, recalling some contents from recent literature contributions. From the articles, it emerges that there are various developments in progress, which need further improvements. On the modelling side, the increase in the computational speed of the computers is making it possible to implement detailed FEM representations, also in 3D, of cable structures with the surrounding soil and ambient also in non-uniform conditions. However, there is also an interesting development of improved models and simplified models that can provide results comparable with FEM.

Some weaknesses of the existing approaches will have to be addressed in future research. The inaccuracy of modelling the presence of points inside the cable structure that cannot be represented with cylindrical symmetry needs more modelling efforts to be addressed. The high burden of the computational procedures based on 3D FEM has to be considered by developing accurate ways to organise the data. There is a need of representing the changes in time of the operational parameters in more effective ways, resorting to experimental validations. Cable monitoring has to be enhanced on the technological side and on developing more refined data analysis tools. The integration of physical and statistical models, as well as the application of more detailed models and/or solution methods with better performance, will improve the accuracy of DCR forecasting.

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