21, rue d'Artois, F-75008 PARIS
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A FEM Case Study of Cable Ampacity Versus Laying Depth and Time

B.C. RUTHERFORD*
Burns & McDonnell
USA

N. ROCHEL
Burns & McDonnell
USA

SUMMARY

The time dependent performance of cable systems has been a topic of debate and research since the 1950's [1]. Additional work around the thermal time constants of deeply installed cables using closed form mathematical methods to account for time dependency as an effective burial depth was accomplished in [2]. Although quite a bit of analytical work has been done to date, little to no work has presented a parametric study of time versus laying depth using a full physics finite element method (FEM) cable model along with content to establish the FEM model technical accuracy.

In today's market with increasing electrical demands, increasing project complexity, and increasing project costs, it is important to optimize cable systems to find effective and efficient solutions. Leveraging modern analysis tools and computational power to evaluate time based, physics driven ampacity calculations, may lead to cost saving or performance enhancing optimization of these cable systems. While not every scenario or installation condition may benefit from detailed FEM modeling, this paper serves to highlight one scenario where efficiency gains may be possible.

This paper presents a discussion of FEM modeling strategies for both time invariant and time dependent modeling to highlight potential optimization of cable systems through modern multi-physics tools. Through this process this paper will summarize the iterative approach taken utilizing FEM tools to determine the following:

- Permissible cable ampacity as a function of time and depth for the case of a 3-core cable
- Comparison to existing IEC calculation methodologies,
- Potential optimization of cable ratings
    - Taking advantage of the large thermal mass and time constants associated with these deeply installed cables.

KEYWORDS

Deeply Installed Cables, Deeply Buried Cables, Underground Transmission, Submarine, Finite Element Modeling, FEM

bcrutherford@burnsmcd.com

1. Introduction

Future looking power grid strategies are driving significant increases in underground power cables for many factors including improved reliability and lower maintenance. These future strategies often occur in populated areas where below ground environments are congested with existing utilities such as water, sewer, gas, telecom, and other buried power cables. Avoiding the existing below grade infrastructure often means installing new cable systems deeper underground. For the purpose of this paper “deeply installed cables” generally refers to cables installed at a depth of 5m or greater.

Additionally, underground cable systems are often used with renewable energy embodiments, such as submarine cables for offshore windfarms. These submarine cable systems typically run long distances buried in the ocean floor to bring the power back to land. At the point of shore landing these cables may have to be 20m deep or greater to avoid existing infrastructure, ecological concerns, or for constructability.

Regardless of the cable use case or installation method, the goal of an underground cable system is to reliably transmit as much energy as possible. Transmitting as much energy as possible means the cable system must be able to transmit as much current as possible. Conventional methodology for calculating cable ampacity is to follow the calculation methods defined by International Electrotechnical Commission (IEC) standards such as [3] and [4]. These conventional standards are time invariant, assuming infinite time; however, real systems and real environments are time varying.

The time dependent performance of cable systems has been a topic of debate and research since the 1950’s [1]. Additional work around the thermal time constants of deeply installed cables using closed form mathematical methods to account for time dependency as an effective burial depth was accomplished in [2]. Although quite a bit of analytical work has been done to date, little to no work has yet to be presented with a parametric study of time versus laying depth using a full physics finite element method (FEM) cable model along with content to establish the FEM model technical accuracy.

2. FEM Modeling Strategy

The approach herein was to develop a FEM cable model with technical correlation to current industry standard methods, and then use that model to evaluate both time invariant and time dependent thermal performance resulting from changes in both cable laying depth and ampacity. The cable model selected for evaluation was the 3-core submarine cable presented in case study 8 of [5] (referred to herein as “case study 8”).

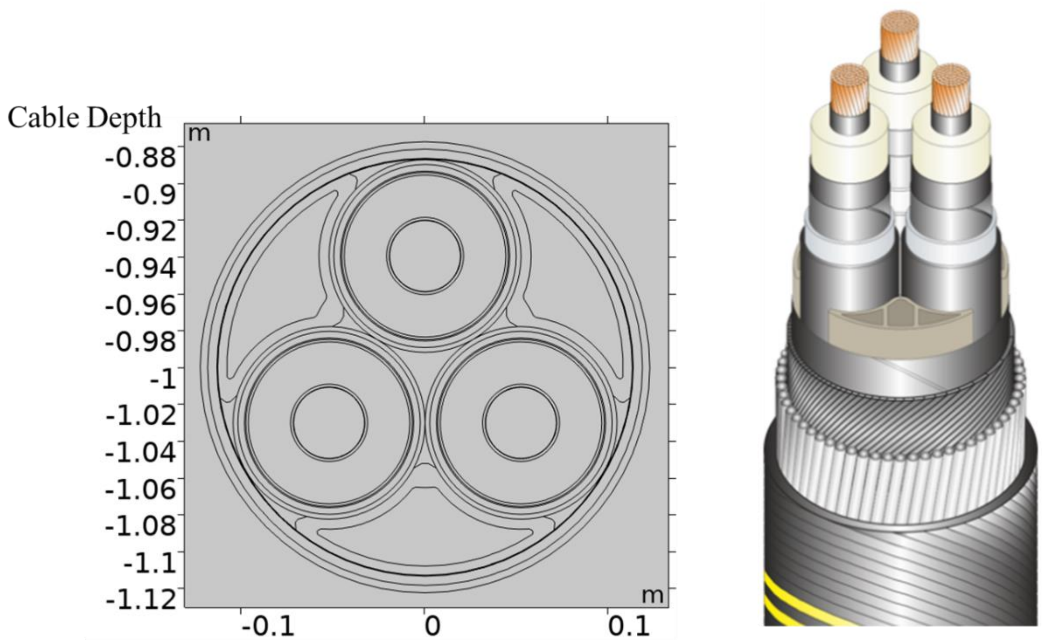
The use of case study 8 provided extensive details on both the cable parameters and the respective IEC current rating calculations from [3] and [4]. The detailed breakdown of each calculation as well as the example ampacity iteration at the end of case study 8 facilitate model comparison. Additionally, with case study 8 being a direct bury scenario, there were no duct bank or conduit components to complicate the model. The simplicity of direct bury allowed a more focused study into the time dependent impact of cable installation depth.

Industry standards are continually updated and revised, as such this paper does not present an investigation into the validity of industry standard calculation methods. This paper focuses on the implementation of the current methodology for a comparative study of cable depth and ampacity versus time. It is not an investigation into the IEC60287 calculation methodology.

FEM Model Equivalency

Before beginning an extensive simulation campaign with an FEM model, it is fundamentally important to validate the equivalency of the FEM model against existing industry standards and technical documentation. For the study contained herein, a FEM model was created using the exact same dimensions, material properties, and geometric factors as case study 8. Figure 1 presents a comparison of the FEM cable geometry and the cable used in case study 8. Additionally, from Figure 1a it can be observed that the 3-core cable in the FEM model has a laying depth of 1m.

The IEC60287 formulas and calculations from case study 8 were replicated directly inside the FEM tool. The FEM embedded IEC60287 calculated results of Table 1 were calcuated using the dimensions and material properties directly from the FEM model parameters. The end of case study 8 presents multiple iterations of IEC60287 ampacity calculations to arrive at a “final” estimated ampacity. Table 1 presents a side by side comparison of the thermal resistances and resulting ampacity of the first iteration of case study 8 caclulations and the equivalent FEM calculated values. From this comparison, it is clear to one skilled in the art that the FEM model has reasonable technical equivalency in both geometry and material properties to case study 8.



(a) (b)

Figure 1 – FEM Model Equivalency: (a) FEM 3-Core Submarine Cable Model of the Cable from Case Study 8 of [1], (b) Cable Image from Figure 40 of Case Study 8 of [5]

When the FEM simulations are performed they will be using the physics engine within the FEM tool, not the wrote IEC60287 formulas used in case study 8. The formula based calculation comparison presented in Table 1 is used to establish reasonable FEM model equivalence.

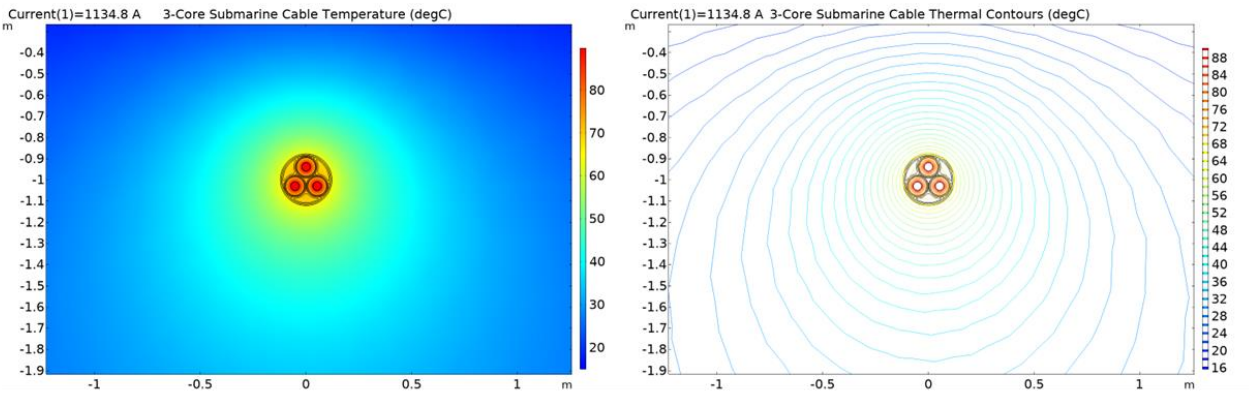
Table 1 – FEM Model Equivalency: Comparison of Calculated Values Thermal Resistance and Ampacity, First Iteration

Case Study 8 of [5] **Parameter**	**Case Study 8 of** [5]	**FEM Model, Calculated**
T_1	0.487287 K·m/W	0.48729 K·m/W
T_2	0.0264137 K·m/W	0.026414 K·m/W
T_3	0.031702 K·m/W	0.03171 K·m/W
T_4	0.31072 K·m/W	0.31075 K·m/W
IEC First Iteration Current	1133.72 A	1133.7 A

For additional FEM model equivalence, a full physics-based FEM simulation was performed using the final IEC60287 iteration current values of case study 8. As shown in Table 2, the FEM model reached a time invariant maximum conductor temperature reached 89.798^{o}C when simulated at case study 8 final iteration current of 1134.82 Amps (A). The heat map and thermal contours of the FEM simulation can be seen in Figure 2.

Table 2 – FEM Model Equivalency: Case Study 8 of [5] Final Iteration Values and FEM Simulated Values

	Case Study 8 of [5]	**FEM Model, Simulated**
Applied Ampacity	1134.81966 A	1134.82 A
Maximum Conductor Temperature	90^{o}C	89.798^{o}C



(a) (b)

Figure 2 – FEM Model Equivalency: Depth = 1m and Current = 1134.82A (a) FEM Simulation Heat Map, (b) FEM Simulation Thermal Contours

It should be noted that case study 8 does not state that the final iteration of conductor temperature is 90^{o}C. This value is being inferred for study purposes due to the industry standard high voltage alternating current (HVAC) cross-linked polyethylene (XLPE) insulated cables maximum conductor temperature of 90^{o}C.

The FEM simulation maximum conductor temperature of Table 2 was found to be 89.798^{o}C, which results in 0.2% error compared to the 90^{o}C case study 8 value. As a result, for correlation to the IEC 90^{o}C mark, from herein the FEM simulations and iterations will use a FEM target maximum conductor temperature value of 89.8^{o}C.

Time Invariant Ampacity Strategy

The time-invariant (stationary) strategy was to perform FEM full physics iterations at a depth while adaptively adjusting the FEM cable current until the maximum conductor temperature met or exceeded the target temperature value of 89.8^{o}C within a small threshold. This was done as a form of "calibration" to maintain case study 8 final iteration 90^{o}C equivalency at each depth. The resulting FEM cable current was recorded, the FEM model cable laying depth was increased (deeper), and the current iterations were performed again.

Time invariant FEM iterations were performed to arrive at a final FEM time invariant cable current. At each depth the FEM model required a starting current value. This starting current, referred to herein as the "IEC Current", came from replicating the first iteration of case study 8 calculations of [3] and [4] directly embedded within the FEM model. The IEC current was calculated at each cable laying depth and recorded for comparison.

Using an FEM embedded IEC current calculation approach helped ensure the final FEM simulation currents would be determined with the same parameters, material properties, and model geometry used for IEC current calculations. The final FEM stationary current values would later be used as the starting current for the time dependent FEM simulations.

All the soil properties were held constant for each iteration at each laying depth. Although it is known that soil temperature changes slightly with increasing depth, by holding the soil temperature, thermal resistance, diffusivity, specific heat, and density constant, this study eliminates degrees of freedom and focuses on the comparison of ampacity versus depth and time.

Time Dependent Ampacity Strategy

Similar to the time invariant strategy, the time dependent strategy involved adjusting the cable laying depth and then iteratively running FEM full physics simulations with adaptively adjusted cable current until a maximum transient conductor temperature of 89.8ºC +/- 0.055ºC was achieved. At each cable laying depth, the initial current value was the final stationary value at the same depth. The conductor temperature transient response was recorded for the initial FEM cable current (baseline scenario) and the final FEM cable current at temperature.

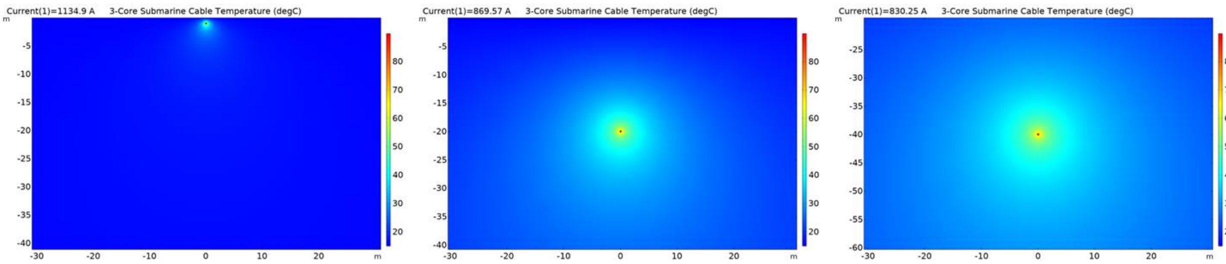
The time dependent FEM simulations were run over a 40-year time span using time step sizes of 0.01 years, which resulted in 4,000 data points per time study. The same cable laying depths were used as the stationary strategy. For each iteration the current was applied as a step function with the entire current value applied at time t=0, and then held constant for the duration of simulation.

The intent of this strategy is to analyze how cable system operational temperature changes over time at a given depth. The purpose of using the maximum conductor temperature at the end of the 40-year span is to benchmark each cable laying depth against the same criteria.

3. Results and Discussion

Time Invariant Results

Figure 3 presents a side-by-side comparison of the same 3-core submarine cable model at increasing laying depth with the respective stationary FEM 89.8ºC current for that depth. The depicted thermal gradient of the figure helps to show the diffusion of thermal energy from a single 3-core cable which would result in mutual heating in a multi-cable or multi-circuit system.



(a) 1m (b) 20m (c) 40m

Figure 3 – Time Invariant FEM Thermal Profile at Depth: (a) Cable Laying Depth of 1m at a Current of 1133.932A, (b) Cable Laying Depth of 20m at a Current of 869.567A, and (c) Cable Laying Depth of 40m at a Current of 830.247A

The FEM calculated IEC currents, time invariant final iteration FEM currents, and their respective final maximum conductor temperatures are captured in Table 3. This table demonstrates the value of using modern computational tools. At a minimum, it can be seen from Table 3 for deeply installed cables that the legacy IEC formula-based ampacity approach is potentially underestimating cable ampacity by several amps, and that the ampacity delta increases with installation depth.

Table 3 – Time Invariant IEC and FEM Ampacity Results with Resulting FEM Temperature

Depth (m)	I_{IEC} (A)	$I_{FEM\text{-}Static}$ (A)	$I_{FEM\text{-}Static} - I_{IEC}$ (A)	$T_{FEM\text{-}Static}$ (°C)
1	1133.682	1134.932	1.250	89.811
5	963.6572	967.157	3.500	89.813
10	910.3837	914.634	4.250	89.834
15	882.9164	887.416	4.500	89.803
20	864.8168	869.567	4.750	89.806
25	851.4902	856.490	5.000	89.829
30	841.0289	846.029	5.000	89.827
35	832.466	837.466	5.000	89.821
40	825.247	830.247	5.000	89.813
45	819.0261	824.026	5.000	89.816
50	813.5735	818.574	5.000	89.801
55	808.7295	813.979	5.250	89.830
60	804.3784	809.628	5.250	89.807

Time Dependent Results

The final FEM current results of the 40-year span transient iterations are shown in Table 4 along with their resulting maximum conductor temperature after 40 years. Recall the adjusted ampacity iterations were performed at each depth until the maximum conductor temperature reached 89.8°C ± 0.05°C.

Table 4 – Final Time Dependent 40 Year Duration FEM Simulation Maximum Ampacity and FEM Temperature

Depth (m)	$I_{FEM\text{-}Time}$ (A)	$T_{FEM\text{-}Time}$ (°C)
1	1134.932	89.8018
5	969.157	89.8443
10	920.690	89.8084
15	899.426	89.7614
20	888.792	89.8053
25	882.932	89.7978
30	880.269	89.8372
35	879.109	89.8470
40	878.131	89.7949
45	877.878	89.8039
50	877.838	89.8191
55	877.750	89.8103
60	877.652	89.7866

A comparative summary of both stationary and time dependent final ampacity results is presented in Table 5. By examining Table 5 it can be observed that the inclusion of time and transient analyses provides potentially significant increases in permissible cable ampacity even at relatively shallow depths.

Table 5 – Complete Comparison of Study Ampacity Values with Time Dependent Ampacity Delta Vs. Stationary Currents

Depth (m)	I_{IEC} (A)	$I_{FEM\text{-}Static}$ (A)	$I_{FEM\text{-}Time}$ (A)	$I_{FEM\text{-}Time} - I_{IEC}$ (A)	$I_{FEM\text{-}Time} - I_{FEM\text{-}Static}$ (A)
1	1133.682	1134.932	1134.932	1.250	0.000
5	963.6572	967.157	969.157	5.500	2.000
10	910.3837	914.634	920.690	10.306	6.056
15	882.9164	887.416	899.426	16.510	12.010
20	864.8168	869.567	888.792	23.975	19.225
25	851.4902	856.490	882.932	31.442	26.442
30	841.0289	846.029	880.269	39.240	34.240
35	832.466	837.466	879.109	46.643	41.643
40	825.247	830.247	878.131	52.884	47.884
45	819.0261	824.026	877.878	58.852	53.852
50	813.5735	818.574	877.838	64.264	59.264
55	808.7295	813.979	877.750	69.021	63.771
60	804.3784	809.628	877.652	73.273	68.023

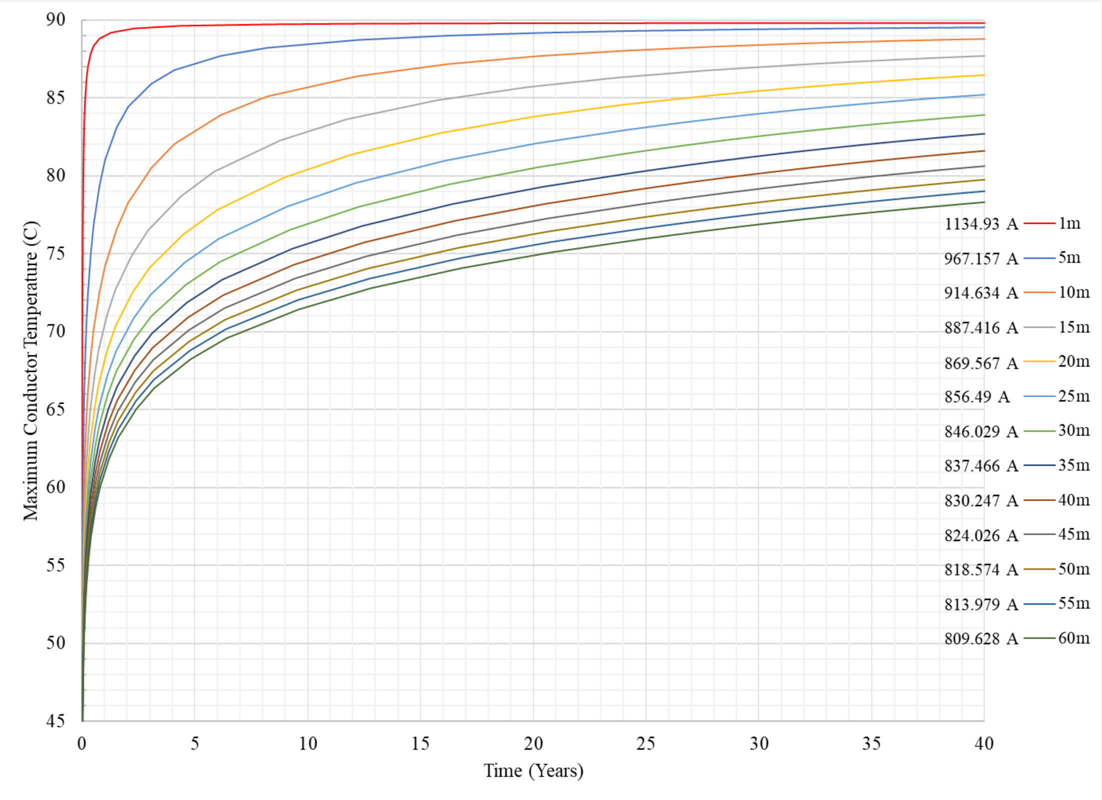


Figure 4 – Time Dependent Baseline FEM Current at First Iteration: 3-Core Cable Conductor Temperature Vs. Depth and Time after 40 years of Continuous Loading

Figure 4 shows the 40-year transient response of applying the static FEM current while Figure 5 presents the transient response curve of the FEM model with the cable driven by the final FEM time dependent current adjusted to achieve 89.8°C at 40-years for each respective laying depth. Recall that in both the baseline and final iteration data, the cable current values were applied as a step function at t=0. The curves of Figure 4 show a similar logarithmic slope versus time and depth as the work presented in [2]. Although the starting soil temperature was 15°C, the y-axes were truncated to 45°C to help separate the curves.

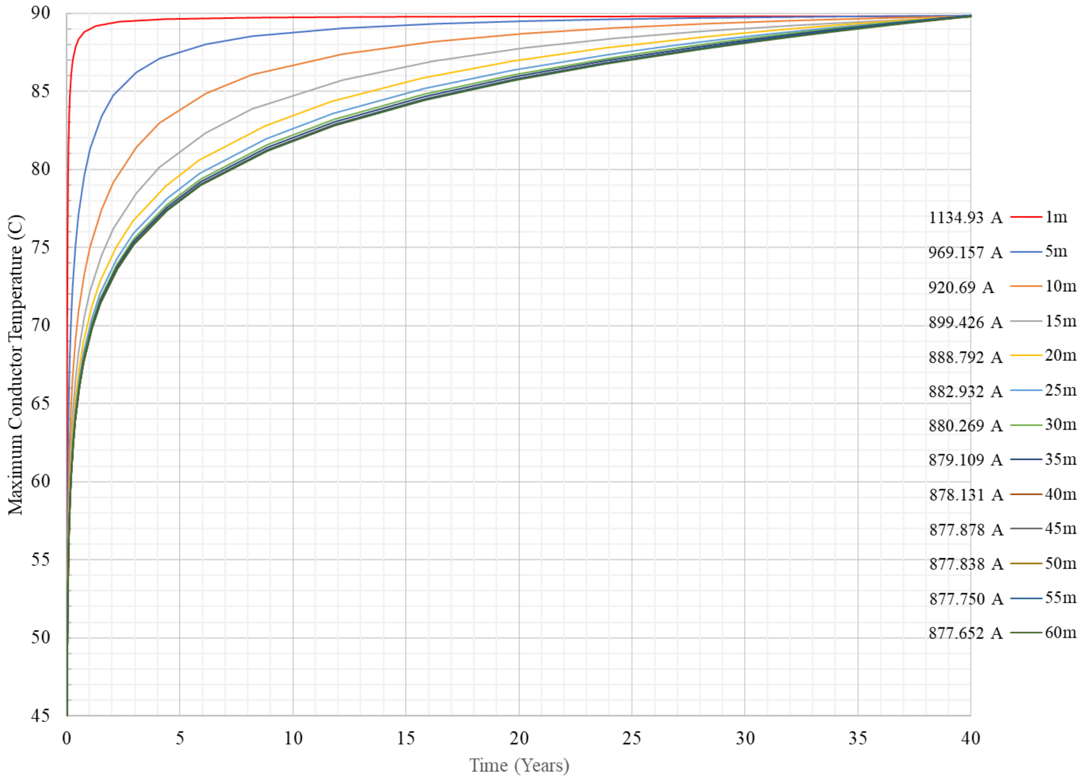


Figure 5 – Time Dependent Adjusted FEM Current at Final Iteration: 3-Core Cable Conductor Temperature Vs. Depth and Time after 40 years of Continuous Loading

Figure 5 demonstrates that considering the transient conditions of a cable installation allows for the cable current to be adjusted to converge at a targeted thermal limit at the end of the cables operational lifespan, and that these cable current adjustments could be significant increases in ampacity. Although an operational cable lifespan of 40 years was herein, this span could be adjusted as needed.

Looking over the collective cable laying depth results at 1m, it can be observed that the conventional calculation methods of [3] and [4] reasonably estimate cable ampacity and thermal performance at a laying depth of 1m. As such, Table 6 presents all the time dependent final FEM 40-year cable current values normalized by the final FEM stationary current at a depth of 1m for a single 3-core submarine cable.

Table 6 – Time Dependent Single 3-Core Submarine Cable 1m Ampacity Normalized Deep Laying Depth Current Adjustment Ratio After 40 Years of Continuous Loading

Depth (m)	Normalized Ratio $I_{FEM\text{-}Time}$ / max($I_{FEM\text{-}Time}$)
1	1.0000
5	0.8539
10	0.8112
15	0.7925
20	0.7831
25	0.7780
30	0.7756
35	0.7746
40	0.7737
45	0.7735
50	0.7735
55	0.7734
60	0.7733

As shown in (1), one can then use the values of Table 6 (Δ_{Depth}) to estimate the equivalent ampacity at laying depths below 1m by first calculating the cable ampacity at a depth of 1m using the methods of [3] and [4], and then multiplying the 1m ampacity by the value of Table 6 which corresponds to the desired laying depth. In theory, one could calculate the IEC60287 ampacity of a single core submarine cable at a laying depth of 1m and then use (1) to estimate the equivalent time dependent ampacity at increased depths.

$$I_{AtDepth} = I_{1m} * \Delta_{Depth} \qquad (1)$$

Figure 6 is the plotted curve of the data captured in Table 6, and could be used to estimate interpolated values of Δ_{Depth} for alternate scenarios of single 3-core submarine cables.

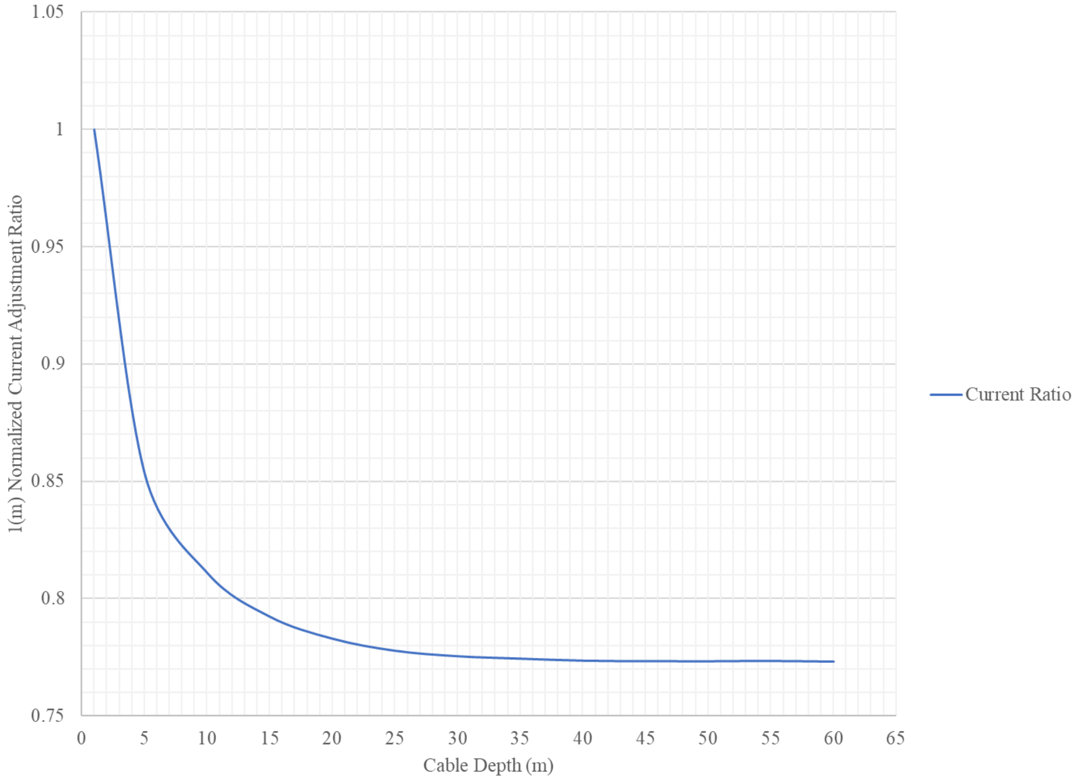


Figure 6 – Ratio of Cable Current at 1m Deep to Cable Current at Increasing Cable Depths to Achieve a Maximum Conductor Temperature of 89.8C After 40 Years of Continuous Loading for a Single 3-Core Submarine Cable

The data captured herein is for a single 3-core cable. The same iterative approach could be repeated in any cable configuration or installation scenario, factoring in situational and project specific criteria. Additionally, all the time dependent scenarios presented in this paper were ran using the industry typical 40-year time period; however, the exact time span could easily be adjusted, shortened or lengthened, to accommodate various levels of design conservatism and risk.

4. Conclusion

By leveraging modern analysis tools and computational power to evaluate time based, physics driven ampacity calculations, solutions may be identified that lead to cost saving or performance enhancing optimization of cable systems. While not every scenario or installation condition may benefit from detailed FEM modeling, the information presented in this paper serves to highlight one scenario where efficiency gains may be possible.

The FEM based study on ampacity and thermal performance of the 3-core submarine cable of case study 8 of [5] has shown that for deeply installed cable systems the legacy formula-based calculation methods could easily underestimate possible cable ampacity. Conversely, from a practical perspective it also indicates that cables may be oversized for certain installation scenarios. Additionally, from the submarine cable ampacity results presented which demonstrate the value of using modern time dependent physics-based FEM methods over static time-invariant calculations, one can conclude that while legacy calculation methods may work reasonably well for cable systems with shallow laying depths around 1m, that with increasing depth more modern methods, such as FEM facilitate potential increases in ampacity and improve system analysis.

Future work using FEM methods should focus on similar studies for scenarios utilizing different duct designs and scenarios with multiple cables where mutual heating becomes significantly impactful. Additionally, future work should focus on expanding the FEM model to incorporate above grade temporal thermal conditions (i.e., solar patterns) and below grade soil conditions could be modeled as time and position dependent gradients.

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