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*RESEARCH ARTICLE*

**An ethical committee approval and/or legal/special permission has not been required within the scope of this study.*

# THERMAL ANALYSIS OF XLPE INSULATED SUBMARINE CABLES FOR DIFFERENT LOADING CONDITIONS

**Ahmet Yigit ARABUL[1,3]***
**Celal Fadil KUMRU[2,3]**

[1]*Yildiz Technical University, Department of Electrical Engineering, Istanbul, Türkiye, arabul@yildiz.edu.tr*

[2]*Suleyman Demirel University, Department of Electrical-Electronics Engineering, Isparta, Türkiye, celalkumru@sdu.edu.tr*

[3]*University of Waterloo, Electrical and Computer Engineering, Waterloo, ON, Canada*

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*Ahmet Yigit ARABUL, Celal Fadil KUMRU*

## ABSTRACT

*Submarine cables are critical assets that play an indispensable role in interconnected power systems, particularly in cross-sea energy transmission and offshore wind turbines. Their importance is further accentuated in exigent situations such as natural disasters and war, which emphasize the need for secure, reliable and uninterrupted energy supply. Furthermore, the investment and operating costs of submarine cables are relatively higher than other power system equipment, making it essential to operate them under the rated operating conditions to prevent possible faults and ensure power system stability. As thermal stress can lead to damage of cable insulation, it is an essential parameter to consider. Overloading increases thermal stress, resulting in rapid aging of the cable insulation and a shorter cable lifetime. Therefore, it is imperative to determine the maximum conductor temperatures and current carrying capacities of submarine cables under varying loading rates and ambient conditions using thermal analysis. In this study, thermal analyses are carried out for a three-phase, 220 kV HVAC, XLPE insulated submarine cable under different loading conditions. The findings demonstrate that the maximum temperature, current carrying capacity, and total losses of the cable are significantly impacted by loading rate, phase imbalance, and seawater temperature.*

**Keywords:** *Submarine cable, thermal analysis, loading rate, offshore wind turbine.*

# FARKLI YÜKLEME ŞARTLARI İÇİN XLPE İZOLELİ DENİZALTI KABLOLARININ ISIL ANALİZİ


## ÖZ

*Denizaltı kabloları, enterkonnekte güç sistemlerinin en önemli ve kıymetli varlıklarından biri olup hem deniz aşırı enerji iletiminde hem de açık deniz rüzgar türbinlerinde yaygın biçimde kullanılmaktadır. Bu kablolar, özellikle doğal afet ve savaş gibi kritik ve stratejik durumlarda daha da önem kazanmaktadır. Ayrıca denizaltı kablolarının hem yatırım ve hem de işletme maliyetleri diğer güç sistem ekipmanlarına kıyasla ciddi derecede yüksektir. Bu sebeplerden ötürü, kablonun nominal işletme şartları içerisinde çalıştırılması ve böylelikle olası arızaların engellenmesi güç sistem kararlılığının sağlanması bakımından elzemdir. Kablo izolasyonun zarar görmemesi için dikkat edilmesi gereken en önemli parametreler arasında ısıl zorlanma gelmektedir. Aşırı yüklenmeye bağlı artan ısıl zorlanmayla kablo yalıtkanı daha hızlı yaşlanmakta ve kablonun işletme ömrü azalmaktadır. Bu nedenle, denizaltı kablolarının farklı yüklenme oranları ve ortam şartları için maksimum iletken sıcaklıklarının ve akım taşıma kapasitelerinin ısıl analizler yardımıyla belirlenmesi önem arz etmektedir. Bu çalışmada, üç faz, 220 kV HVAC, XLPE izoleli bir denizaltı kablosunun farklı yüklenme koşulları altında ısıl analizleri gerçekleştirilmiştir. Sonuçlar, yüklenme oranının, faz dengesizliğinin ve deniz suyu sıcaklığının kablonun maksimum sıcaklığı, akım taşıma kapasitesi ve toplam kayıpları üzerinde önemli etkisi olduğunu göstermektedir.*


**Anahtar Kelimeler:** *Denizaltı kablosu, ısıl analiz, yüklenme oranı, açık deniz rüzgar türbinleri.*

## 1. INTRODUCTION

Energy is a critical issue in modern society and its significance continues to grow with advancements in technology and increasing energy demands. Distributed generation facilities such as wind and solar power plants, as well as alternative energy sources, are being utilized to meet the rising energy demand in the most expedient and practical manner (Keskin Arabul et al., 2017). Offshore wind power plants have become increasingly popular in many countries due to their high energy production capacity. The literature and practice have seen numerous studies conducted to enhance the efficient use of energy resources. Despite these efforts, natural disasters and wars can lead to critical situations where the energy supply-demand balance cannot be maintained. While the occurrence probability of natural disasters such as earthquakes, floods, and hurricanes is low, their effects on the power system can be quite severe. In such scenarios, the existence of an interconnected network with submarine cables is vital in meeting energy needs.

Submarine cables are extensively used for energy transfer in interconnected networks, with approximately 1.3 million kilometers of such cables installed worldwide at different voltage levels (*Submarine Cable Almanac*, 2021). Guides and standards for the design, production, installation, and operation of submarine cables have been established and are presently in use (IEEE, 2004). However, the nominal operating ranges may vary based on factors such as cable type (AC or DC), voltage level, and ambient conditions in the installation region. In particular, it is critical to analyze parameters such as maximum operating temperature, ampacity, and critical loading rate in detail, depending on the cable type and the region. Another important aspect in submarine cable selection is determining whether energy transmission will be through AC or DC cable. Recent studies show that the topic of energy transmission through DC submarine cables has gained significant popularity (Hu et al., 2014; Lldstad, 1994; Mei et al., 2017; Zhang et al., 2021). Literature and practical examples reveal that optimal system design is performed based on the power to be transmitted, transmission distance, and investment cost (Takeshita et al., 2022). Submarine cables have a critical role in maintaining power system reliability, and their investment costs are quite high. Therefore, online monitoring of cable conditions is crucial to prevent unexpected faults (Ou et al., 2022). One of the primary reasons for submarine cable failure is thermal stress (Mei et al., 2017; Yu et al., 2022). In cases of excessive or unbalanced loading, thermal stress on cable insulation can increase, leading to a decrease in the cable's life. Consequently, there is a need for studies to determine cable operating limits for different loading conditions.

This study conducts thermal analyses of a three-phase, 220 kV, and 500 mm$^2$ submarine cable for various loading and environmental conditions, utilizing the COMSOL® Multiphysics 5.6 software. The study determines conductor, screen, and armor losses, as well as maximum and minimum operating temperatures under different loading rates, unbalanced loading conditions, and various seawater temperatures. Furthermore, cable's ampacity is calculated for various loading conditions, and the results obtained discussed.

## 2. METHODOLOGY AND MATERIAL

In this study, a numerical model of a lead-shielded, XLPE-insulated, three phase HVAC submarine cable with a nominal voltage of 220 kV is utilized for thermal analysis (COMSOL, 2023). The cable utilizes copper conductors with a phase conductor cross section of 500 mm$^2$ and a nominal current carrying capacity of 655 A. The design of the cable is modeled in 2D and is depicted in Figure 1.

The cable illustrated in Figure 1 has been installed 7 cm beneath the seabed on a bed of gravel. In this study, frequency domain analyses are conducted utilizing the “Magnetic Fields” and “Heat Transfer in Solids” interfaces. Conductor losses, shield losses, and armor losses due to phase currents are calculated by taking into account the inductive effects within the Magnetic Fields interface. These losses are defined as the heat source in the Heat Transfer in Solids interface, and temperature distributions within the cable are obtained. This approach enabled the establishment of a multiphysics coupling between electromagnetic fields and heat transfer by utilizing a frequency-stationary study type. Material properties and boundary conditions are defined with reference to the COMSOL® Multiphysics 5.6 library.

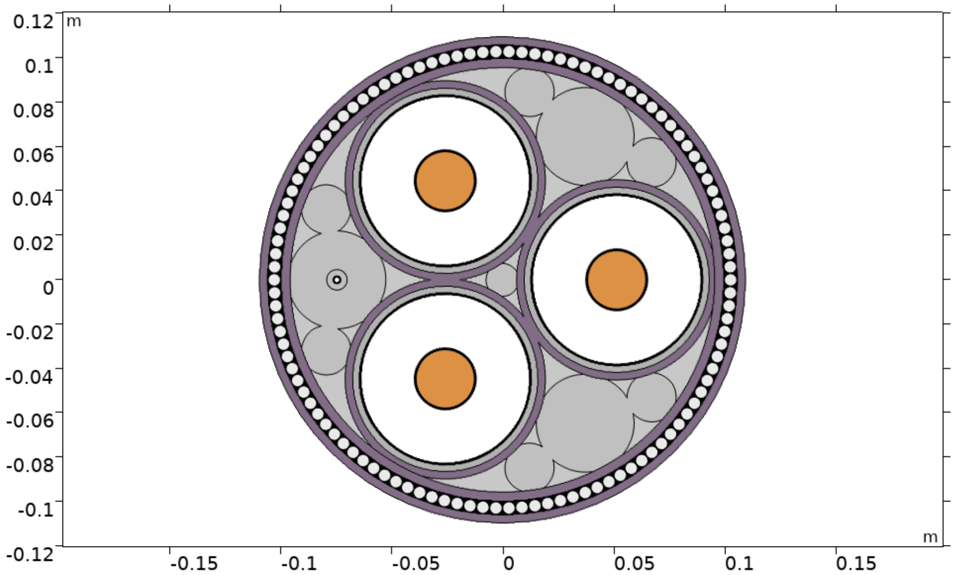


**Figure 1.** 2D geometry of three phase, 220 kV HVAC submarine cable used in the analyses.

The aim of this study is to investigate the effects of three different conditions on cable temperature, namely, loading ratio, unbalanced loading, and seawater temperature, on the cable's maximum temperature, ampacity, and total losses. Further details of the analyses are presented in Table 1.

**Table 1.** Description of analyses performed in the study.

| Analysis | Description |
|---|---|
| Loading rate | Three phases are loaded from 50% to 120% with 10% steps |
| Unbalanced loading | 2 phase is 50% loaded<br>1 phase is loaded from 50% to 120% with 10% steps |
| Seawater temperature | Seawater temperature is changed from 5°C to 30°C with 5°C steps. |

## 3. RESULTS AND DISCUSSION

This section provides a presentation of the outcomes derived from simulation studies conducted on a submarine cable. The examination focuses on three distinct cases. Firstly, simulations are performed to investigate the thermal changes of the cable in both balanced and unbalanced loading conditions. Secondly, the studies are expanded to include simulations conducted under various sea water temperatures.

### 3.1. Effects of Varied Loading Rates

Simulation studies are conducted to explore various loading rates under conditions of balanced loading. In this scenario, the cable is subjected to operational loads ranging from 50% to 120% of its ampacity. The resulting maximum and minimum temperature values observed on the cable are presented in Figure 2.

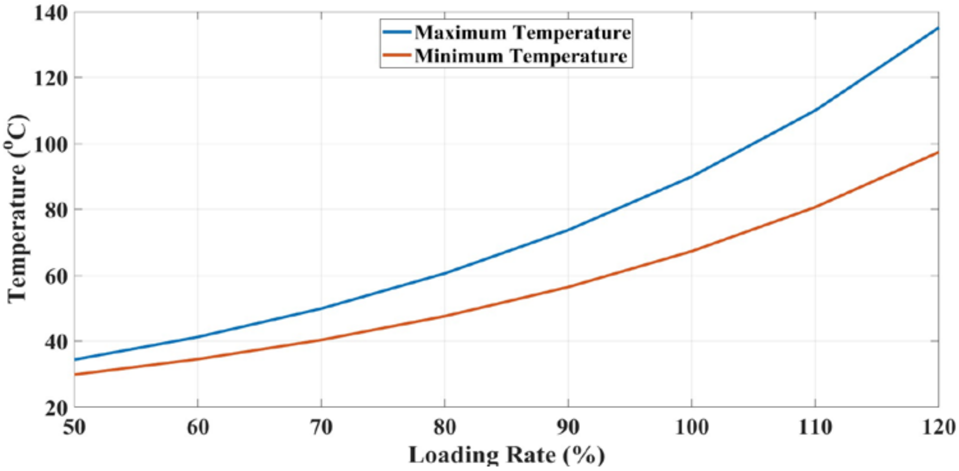


**Figure 2.** Temperature variations in a balanced loads under different loading conditions.

The aforementioned line chart illustrates the maximum and minimum temperatures of the submarine cable in response to various loading rates, ranging from 50% to 120%. It is evident that the temperature changes on the cable are non-linear with respect to changes in load, as the temperature rise is more pronounced at higher loading rates. Moreover, the difference between maximum and minimum temperatures increases from 4.54 °C to 37.77 °C, as depicted by the diverging lines in the graph. Such temperature differences are undesirable, as they may lead to unfavorable deformation of the cable material. Losses, which are a crucial factor impacting temperature increases, are documented in Table 2 for distinct loading conditions under balanced loading.

**Table 2.** Submarine cable losses under different loading rates in a balanced loading.

| Loading Rate (%) | Phase Losses (W/km) | Screen Losses (W/km) | Armor Losses (W/km) |
|---|---|---|---|
| 50 | 10712 | 3254 | 1930 |
| 60 | 16111 | 4616 | 2745 |
| 70 | 23094 | 6166 | 3679 |
| 80 | 32040 | 7872 | 4713 |
| 90 | 43461 | 9691 | 5827 |
| 100 | 58058 | 11570 | 6989 |
| 110 | 76797 | 13447 | 8163 |
| 120 | 101050 | 15241 | 9303 |

The observations from Table 2 indicate that all losses increase in proportion to the loading ratio. Screen and armor losses exhibit a relatively lower rate of increase, while phase losses show a steep rise. The reason for this is the direct proportionality of phase losses to the square of the current. Upon examining the effect of these losses on the overall loss, it is evident that phase losses rise from 67% to 80%, while screen and armor losses drop from 20% to 12% and from 12% to 7%, respectively. The thermal distribution resulting from the operation of a 100% balanced loaded cable is depicted in Figure 3.

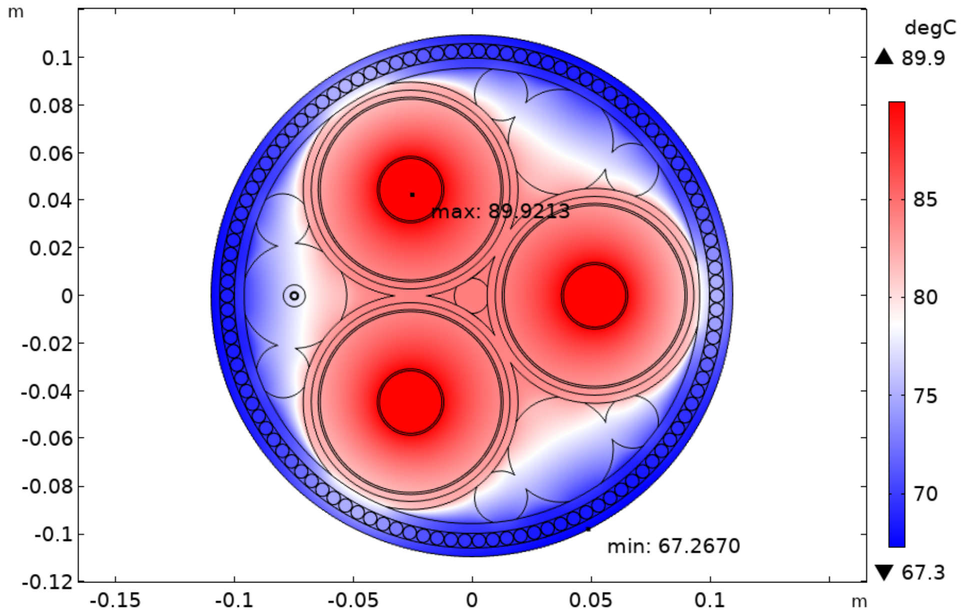


**Figure 3.** Temperature distribution across a cable under 100% balanced loading

### 3.2. Effects of Unbalanced Loading

In this stage of the simulation study, the three-conductor submarine cable is subjected to unbalanced loading by altering the current passing through a single phase. The loading rate of the unbalanced phase is varied between 50% and 120%, while the other two phases are held constant at 50% loading. The maximum and minimum temperatures recorded on the cable under these loading conditions are presented in Figure 4.

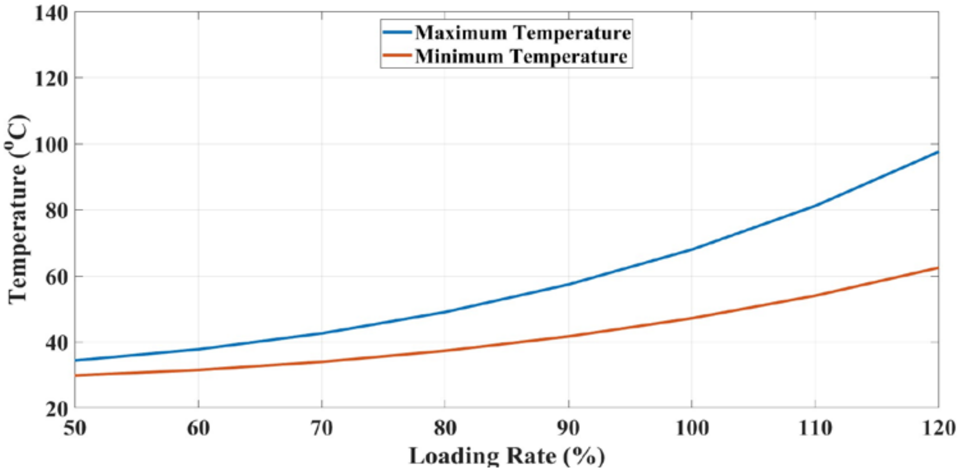


**Figure 4.** Temperature variations in an unbalanced loads under different loading conditions.

As can be observed from Figure 4, the maximum and minimum temperature changes on the cable exhibit a pattern similar to that of the balanced loading. In this figure, it is also noted that the temperature does not increase linearly, but rather increases more as the loading ratio increases. Since the loading rate of the two phases that are constantly loaded is 50% in the case of balanced loading, the temperature values are lower than those of the cable in which all three phases are balanced. In addition, it is observed that the difference between the maximum and minimum temperatures has increased from 4.54 °C to 35.12 °C. Although the maximum and minimum temperature values are lower than those of the balanced loading condition, the difference (Δt) between them is of similar magnitude. Under the conditions where one phase is altered, the cable has a current carrying capacity of up to 1067 A or 15% of its ampacity. Under unbalanced loading conditions, the submarine cable losses for different loading scenarios are presented in Table 3.

**Table 3.** Submarine cable losses under different loading rates in an unbalanced loading.

| Loading Rate (%) | Phase Losses (W/km) | Screen Losses (W/km) | Armor Losses (W/km) |
|---|---|---|---|
| 50 | 10712 | 3254 | 1930 |
| 60 | 12690 | 3847 | 2271 |
| 70 | 15523 | 4788 | 2796 |
| 80 | 19325 | 6080 | 3509 |
| 90 | 24282 | 7729 | 4415 |
| 100 | 30638 | 9746 | 5523 |
| 110 | 38713 | 12145 | 6845 |
| 120 | 48910 | 14943 | 8396 |

Upon examination of Table 3, it is evident that phase losses display a considerably higher rate of increase compared to the screen and armor losses, owing to their direct proportionality with the square of current. Furthermore, when the effect ratios of these losses on the total loss are evaluated, it is seen that the loss ratios do not experience significant variations with the alteration of the loading ratio on one of the phases. The results of this study show that the average percentages of phase losses, screen losses, and armor losses are 67%, 21%, and 12%, respectively. The thermal distribution resulting from the operation of the unbalanced loaded cable, where one phase is loaded at 100% and the other two phases are loaded at 50%, is presented in Figure 5.

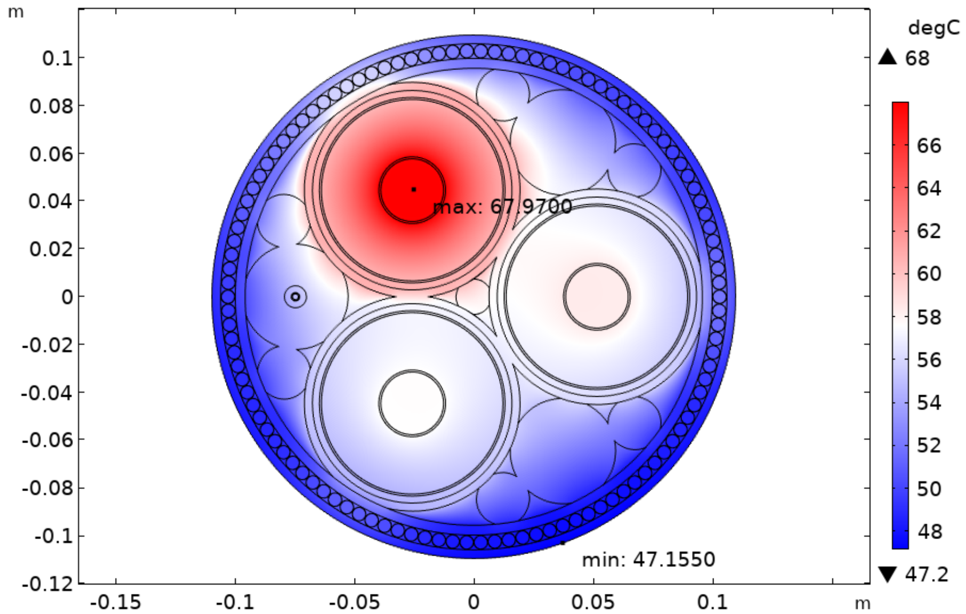


**Figure 5.** Temperature distribution under unbalanced loading: one phase loaded at 100%, other phases at 50%.

### 3.3. Effects of Sea Water Temperature

In this stage of the simulation study, an additional parameter affecting temperature, namely changes in seawater temperature, is investigated. Although seawater temperature is generally assumed to be 20 °C in the literature, fluctuations at this temperature can significantly affect the cable temperature and its ampacity. Therefore, simulations are conducted for seawater temperatures ranging from 5 °C to 30 °C, considering the minimum and maximum temperatures in oceans. The resulting maximum and minimum temperature variations on the cable for different seawater temperatures are depicted in Figure 6.

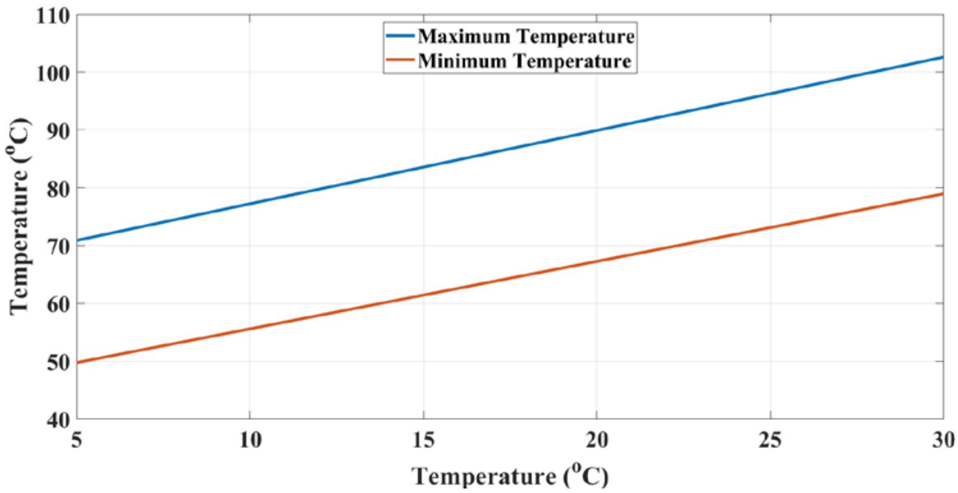


**Figure 6.** Temperature variations in a balanced loads under different seawater temperatures.

As opposed to the simulation results obtained in the previous subsections, it can be observed from Figure 6 that the maximum and minimum temperatures increase almost linearly with increasing seawater temperature. It is also noted that the difference between maximum and minimum temperatures (Δt) changes very slightly between 21.13 °C and 23.66 °C. This low variability in temperature difference is a positive factor for cable insulation. Specifically, it is observed that low seawater temperatures have a positive effect on the cable's current-carrying capacity. For instance, it can carry up to 10.1% more current (i.e., 1021.4 A instead of 927.72 A) under seawater temperature of 5 °C. Conversely, under seawater temperature of 30 °C, the current-carrying capacity decreases by 7.3% (i.e., from 927.72 A to 860 A). The submarine cable losses under these conditions are presented in Table 4.

**Table 4.** Submarine cable losses under different seawater temperatures.

| Seawater Temperature (°C) | Phase Losses (W/km) | Screen Losses (W/km) | Armor Losses (W/km) |
|---|---|---|---|
| 5 | 52782 | 12055 | 7308 |
| 10 | 54546 | 11891 | 7200 |
| 15 | 56304 | 11729 | 7093 |
| 20 | 58058 | 11570 | 6989 |
| 25 | 59806 | 11414 | 6886 |
| 30 | 61550 | 11261 | 6786 |

When considering the ratios of the losses in Table 4 with respect to the total loss, it can be seen that the ratios of phase losses vary between 73% and 77%, while screen losses vary between 16.71% and 14.15%, and armor losses vary between 10% and 8.5%. In the case of seawater temperature being 30 °C, the thermal distribution of the balanced loaded cable is shown in Figure 7.

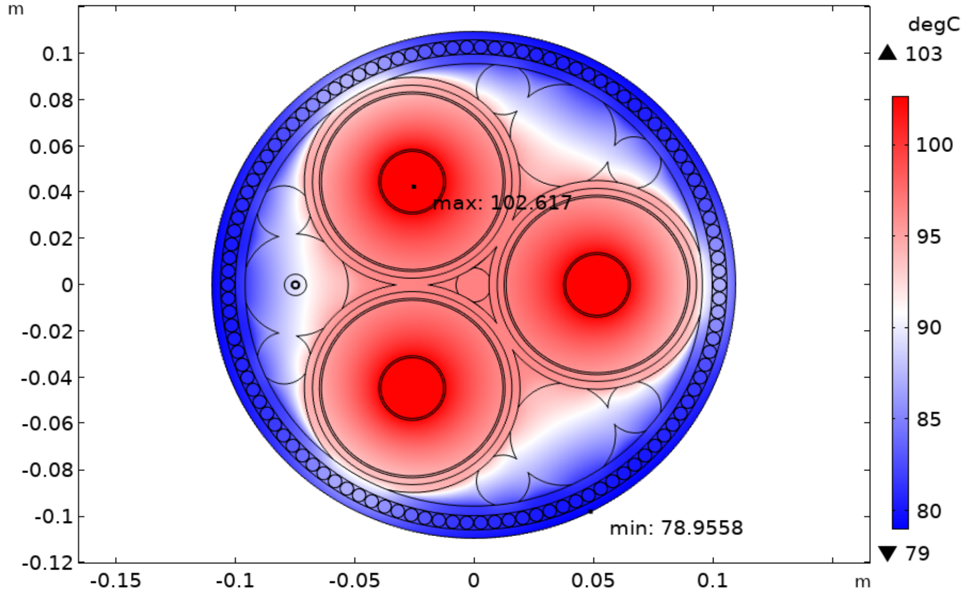


**Figure 7.** Thermal distribution across a 100% balanced loaded cable in 30 °C seawater.

## 4. CONCLUSION

In this study, thermal analyses of a three-phase, 220 kV HVAC, XLPE insulated submarine cable used for offshore wind turbines under different loading conditions are carried out. In simulation studies, it is observed that as the cable's loading value increases at a constant sea temperature, its maximum temperature increases rapidly in a logarithmic manner. Similarly, when the phases are unbalanced, the maximum temperature also increases rapidly in a logarithmic manner. A similar rapid increase is also observed in the Phase Losses, which is related to the $I^2 \times R$ ratio. Additionally, the cable's thermal stress is investigated by analyzing the differences between its maximum and minimum points. The temperature difference (Δt) is found to be the same in the case of balanced operation, where all phases are loaded equally, as well as in the case where only one phase is loaded at high rates while two phases are loaded at 50%.

It is also observed that the current carrying capacity of the cable can increase by 10.1% if the sea water temperature is 15 °C lower than the nominal operating conditions, while it can decrease by 7.3% if the sea water temperature is 10 °C higher. Due to the significant effect of the sea water temperature on the cable's current carrying capacity, it may be considered as a criterion in the location preference during the installation of offshore wind turbines.

**CONFLICT OF INTEREST STATEMENT**
The authors declare no conflict of interest.

## REFERENCES

COMSOL. (2023). *Modeling Cables in COMSOL®: An Electromagnetics Tutorial Series*. https://www.comsol.com/model/cable-tutorial-series-43431

Hu, M., Xie, S., Zhang, J., & Ma, Z. (2014). Desing selection of DC & AC submarine power cable for offshore wind mill. *China International Conference on Electricity Distribution, CICED, 2014-December,* 1675–1679. https://doi.org/10.1109/CICED.2014.6991991

IEEE, 1120-2004. (2004). *1120-2004 IEEE Guide for the Planning, Design, Installation, and Repair of Submarine Power Cable Systems*.

Keskin Arabul, F., Arabul, A. Y., Kumru, C. F., & Boynuegri, A. R. (2017). Providing energy management of a fuel cell–battery–wind turbine–solar panel hybrid off grid smart home system. *International Journal of Hydrogen Energy*, *42*(43). https://doi.org/10.1016/j.ijhydene.2017.02.204

Lldstad, E. (1994). World Record HVDC Submarine Cables. *IEEE Electrical Insulation Magazine*, *10*(4), 64–67. https://doi.org/10.1109/57.298131

Mei, W., Pan, W., Chen, T., Song, G., & Di, J. (2017). Research and design of DC500kV optical fiber composite submarine cable. *4th IEEE International Conference on Engineering Technologies and Applied Sciences, ICETAS 2017*, *2018-January*, 1–6. https://doi.org/10.1109/ICETAS.2017.8277901

Ou, X., Xu, W., Zang, Y., Wang, H., Wu, H., Lv, A., & Zhou, Z. (2022). Mechanical analysis of 500 kV oil-filled submarine power cable in anchor and blade damage based on Finite element method. *IEEE Advanced Information Technology, Electronic and Automation Control Conference (IAEAC)*, *2022-October*, 1068–1072. https://doi.org/10.1109/IAEAC54830.2022.9929551

*Submarine Cable Almanac*. (2021). Global Submarine Cable Network. https://www.submarinecablemap.com/

Takeshita, H., Nakamura, K., Matsuo, Y., Inoue, T., Masuda, D., Hiwatashi, T., Hosokawa, K., Inada, Y., & de Gabory, E. L. T. (2022). Demonstration of Uncoupled 4-Core Multicore Fiber in Submarine Cable Prototype with Integrated Multicore EDFA. *Journal of Lightwave Technology*. https://doi.org/10.1109/JLT.2022.3195190

Yu, X., Zhang, S., Peng, X., Feng, B., Yu, S., Zhu, W., & Deng, J. (2022). Simulation Study on Steady-State Ampacity of ±400 kV J-tube DC Submarine Cable. *Proceedings - 2022 4th International Conference on Electrical Engineering and Control Technologies, CEECT 2022*, 546–551. https://doi.org/10.1109/CEECT55960.2022.10030564

Zhang, H., XIE, S., Hu, M., Zhang, X., Ling, Z., Zhan, H., & Jing, Y. (2021). *Development Prospects of High Economy XLPE Insulation HVDC Submarine Cable*. 1046–1055. https://doi.org/10.1049/ICP.2021.2223