

Active Power Losses in the Crete-Peloponnese Subsea HVAC Interconnection: Insights from One-Year Measurements

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Abstract—In 2021, Crete island was linked for the first time to the Hellenic mainland power grid through a composite submarine and underground cable system. This connection, known as the Crete-Peloponnese interconnection, is the longest submarine/underground alternating current cable interconnection in the world (almost 178 km). Also, it holds the record for the longest (134 km) and deepest (up to 1000 m) submarine high voltage interconnection with a three-core cable of cross-linked polyethylene (XLPE) isolation. It is well known that as the transmission distance increases, the power transfer capacity of such interconnections is reduced due to the existence of cable losses and the higher absorbed reactive power. These losses are typically calculated using analytical and numerical approaches, which in many cases fail to account for the non-homogeneous operational conditions of submarine cables. This paper aims to overcome these limitations and evaluate the submarine cable active power losses through in situ measurements collected over a one-year period. The results indicate that the losses within the cable are within acceptable limits, approximately 6.75% of the total transmitted energy.

Index Terms—HVAC interconnection, power losses, real-world measurements, submarine power cable, XLPE cable.

I. INTRODUCTION

Over the past decades, the Crete power system has faced increasing production costs, load demand growth, challenges in finding suitable sites for new conventional power plants, and low reliability of supply during system failures. Leveraging the island's renewable energy potential could have helped mitigate some of these issues. However, integrating renewable energy sources (RES) is limited by technical constraints, since they cannot serve as primary power supply plants due to their intermittent and stochastic nature [1]. In order to secure Crete's energy supply, improve the quality of electricity, decrease power generation costs (thereby reducing utility bills for consumers), minimize the island's environmental impact, and integrate Crete into the wholesale electricity market, the Independent Power Transmission Operator (IPTO)—operator of the Hellenic Electricity Transmission System—has designed a two-phase project [2], [3]. The first phase, which included the construction of a 150 kV alternating current (ac), 2×200 MVA interconnection between Crete

and the Peloponnese peninsula, has been operational since 2021. The second phase, that involves a high voltage direct current (HVDC) interconnection between Crete and Attica (2×500 MW capability), is scheduled to become operational in 2025. It is worth noting that an international project, namely “The Great Sea Interconnector” is also planned, aiming to establish a HVDC interconnection that will link the electrical grids of Israel, Cyprus, and Greece, including the island of Crete.

Driven by advances in cable technologies, the expansion of offshore wind farms, and the rising interconnection projects between countries, the ac submarine cable market is experiencing significant growth [4]. High voltage ac (HVAC) subsea transmission is generally preferred for shorter distances, due to its simple structure and low cost [4], [5]. This is attributed to the fact that the ability of subsea ac cables to transmit power beyond a certain distance is limited by the existence of electrical losses that depend on several factors such as the characteristics of the cable, installation conditions, and the operational mode of the system [6]. On the contrary, HVDC submarine cables offer greater transmission capacity and lower losses, but their construction and operational expenses are significantly higher [7]; these drawbacks have prompted research into extending the feasibility of HVAC submarine cables [5].

In the literature, transmission losses are typically assessed using the general theoretical background of cable losses, analytical and numerical methods, and extensive simulations [8]–[12]. These approaches estimate total losses by accounting for various types of transmission losses—such as conductor, dielectric, and sheath losses—which depend on cable characteristics (e.g., length and diameter) and operational conditions (e.g., operating temperature, current, and voltage). Nevertheless, these methods hinder the proper evaluation of real-world performance, since they currently do not take into account the non-homogeneity operational characteristics of high voltage (HV) submarine and underground cables (e.g., heat distribution within the cable, voltage fluctuations, etc.), despite their criticality. They also fail to account for the variability of surrounding environmental conditions in subsea and underground settings [13]. Their use is primarily driven by the limited availability of real-world measurements.

Contrary to the literature, this work aims to provide a detailed analysis of active power losses in subsea HVAC cables by exploiting real measurements from an actual

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interconnection, specifically the existing Crete-Peloponnese HVAC interconnection. The interconnection is realised via two HVAC circuits with submarine and underground sections. In both section types, cross linked polyethylene (XLPE) insulated power cables were selected [14]. The analyzed data is used to assess active power losses, based on measurements collected over one year of operation, which are thoroughly examined and discussed. In addition, a comparison between the active power loss profiles of a typical winter and summer day—alongside the corresponding production and demand profiles—is conducted, leading to several useful insights. It is important to highlight that, at the time of writing, this interconnection is the only existing link between the island of Crete, i.e., the largest island in Greece, and the Hellenic mainland.

The rest of this paper is structured as follows: a general description of the structure and features of HV XLPE cables used in the Crete-Peloponnese interconnection is provided in Section II, while Section III presents the technical characteristics of the considered interconnection. A detailed analysis of the interconnection active power losses is performed in Section IV using actual measurements from a 12-month period. Finally, Section V summarizes the main findings of the paper and offers directions for future research.

II. HVAC XLPE POWER CABLES

Aiming to serve electrical power transmission, HV cables are designed to have features, such as high current-carrying capacity, superior insulation properties, reduced infrastructure costs, and strong construction [15]. Power transmission capacity of HVAC power cables is limited by cable's length due to voltage stability reasons. In particular, in long HVAC power cables large amounts of reactive power is produced resulting in increased voltage levels, stressing the cable thermal limits and reducing its active power transfer capability. To maximize power transmission the cable has to be operated with symmetrical voltage profile. To that end, installation of reactive compensation schemes is commonly adopted [16].

Submarine and underground HVAC power transmission pose extra challenges, due to the harsh conditions of the cable's surrounding environment. In submarine applications, in particular, factors such as saltwater exposure, pressure changes, and potential damage of the cables from marine life encumber HVAC power transmission [4]. To overcome those challenges, XLPE insulated cables are often selected due to their numerous advantages. XLPE insulation offers excellent thermal stability and water resistance, a fact that ensures the integrity and reliability of power transmission in submarine environments. In addition, XLPE insulated cables have enhanced durability, ensuring a longer lifetime, while they are also flexible, lightweight, and highly resistant to bending, resulting in easier installation and maintenance. Additionally, XLPE power cables provide superior electrical performance, characterized by high insulation resistance and low dielectric losses. These properties enable XLPE cables to suppress length constraints and derate the effect of reactive power due to their higher operating temperature and consequently greater ampacity [17]. Given the numerous benefits of XLPE HV cables, this type of cable was selected for use in both the underground and submarine sections of the HVAC Crete-Peloponnese interconnection. A cross section of a typical three-core XLPE cable is presented in Fig. 1.

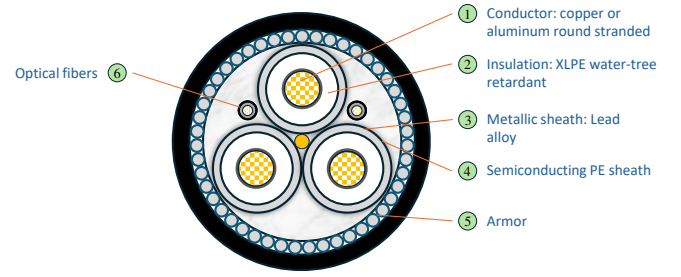


Fig. 1. Cross section of a three-core XLPE cable.

Regarding their structure, each core of XLPE cables consists of a copper or aluminum conductor, which is covered with a layer of XLPE insulation materials. An extra cover, known as the sheath, includes a lead alloy metallic part, as well as a semiconducting part usually made of polyvinyl chloride (PVC) or polyethylene (PE), acting as an additional protection layer and preventing water ingress. The insulation materials are designed to withstand the intense voltage and electrical stress encountered during power transmission. Steel wire or non-magnetic material armoring provides protection against magnetic field losses [18]. Modern cables may also include optical fibers for data transmission.

Power losses in HVAC XLPE cables can arise from a variety of reasons. These include: i) the ac current that flows through the resistance of the conductor resulting in conductor losses, ii) the voltage across the insulation causing dielectric losses, iii) the induced currents in the sheath resulting in sheath losses, iv) the circulating currents in loops formed between sheaths of different phases leading to inter-sheath losses, and v) losses in the protective armoring [19].

III. CASE STUDY: CRETE-PELOPONNESE INTERCONNECTION

In the present study, the ac interconnection between Crete-Peloponnese is investigated regarding the active power losses within a year of its operation. The interconnection is implemented via two identical 150 kV ac circuits consisting of submarine and underground sections, as shown in Fig. 2, that enable a maximum transfer capability of 200 MVA and maximum continuous current flow of 770 A. It includes two submarine cables between the landing points in Peloponnese and Crete, of approximately 134 km length each. The underground cables that connect the landing points with the onshore substations, Sklavouna substation in Peloponnese (S/P) and Chania GIS substation in Crete (S/C), cover a distance of 9.4 and 34 km, respectively, as shown in Fig. 2. The interconnection has four connection points, namely P1 and P2 in Sklavouna substation S/P, and C1 and C2 in Chania GIS substation S/C. The two terminals S/C and S/P have been selected considering the minimization of the submarine route, and consequently the complete project cost and the reactive compensation requirements.

Due to the considerable length and high capacitance of the underground and submarine sections, the link generates significant amounts of reactive power, which decreases the active power transfer capability and increases the voltage level at the terminal stations. In both terminals, S/P and S/C, a reactive power compensation and voltage control scheme has been adopted, consisting of a three-phase static reactor in each connection point (P1, P2, C1, C2) and two variable

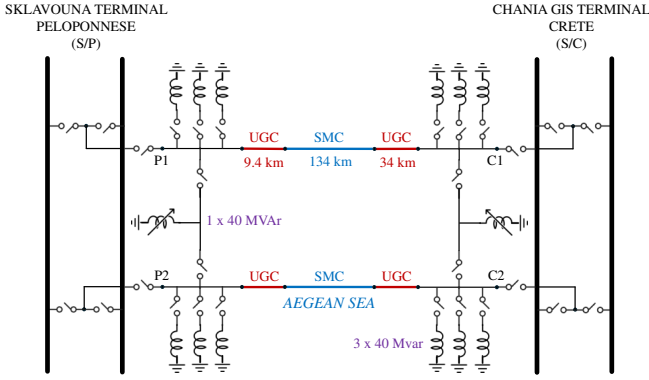


Fig. 2. The 150 kV ac 2x200 MVA Crete-Peloponnese interconnection. UGC and SMC denote the underground and submarine sections of the interconnection, respectively.

three-phase reactors between the connection points of each substation (P1-P2 and C1-C2), as depicted in Fig. 2. Each static reactor consists of three blocks of 40 Mvar nominal capacity, while the variable reactor has a capacity range from almost 0 up to 40 Mvar [20].

As mentioned earlier, both the submarine and underground sections are realized by XLPE type cables. Specifically, in the two submarine sections, three-core power cables have been selected that involve 630 mm² copper conductor, XLPE insulation, lead/PE sheath with double flat. In the four underground sections, single-core power cables have been selected consisting of a 1200 mm² aluminum conductor, XLPE insulation and PE sheath.

The investigation of the interconnection power and energy performance is based on measurements acquired at points P1 and P2 of S/P, and at points C1 and C2 of S/C. Hourly active power measurements over the period of July 1, 2023 to June 30, 2024 are used for the annual analysis, whereas measurements of 1-min timestep are utilized to examine in detail indicative days of the year. It is important to note that the measurements are collected by remote telemetry units (RTUs), which capture the operational states (analogue or digital) of substations from sensors and transmit the data to the SCADA (Supervisory Control and Data Acquisition) system using the HNZ, IEC 60870-5-101, or IEC 60870-5-104 protocols [21].

IV. RESULTS

A statistical analysis of the active power flowing per month through the interconnection as measured at the sending end over the studied period is provided in Fig. 3, in the form of box plots. Note that, since the power flow over the interconnection is bidirectional, the sending end may switch between S/P and S/C several times within the examined period. It is derived that the higher values of active power are observed during the summer months, with a median greater

TABLE I
ANNUAL ANALYSIS OF ACTIVE POWER RECORDED AT THE SENDING END OF THE INTERCONNECTION AND POWER LOSSES

	Maximum	Median	Mean
Power flow	227.1 MW	90.5 MW	82.7 MW
Power losses	12.2 MW	5.4 MW	5.6 MW

TABLE II
ANNUAL ENERGY MEASURED AT THE TWO ENDS OF THE INTERCONNECTION AND ENERGY TRANSFER LOSSES

	Sending end		Receiving end	Losses
S/P	710.0 GWh	S/C	664.7 GWh	45.4 GWh
S/C	14.8 GWh	S/P	11.3 GWh	3.5 GWh
Total	724.8 GWh	Total	676.0 GWh	48.9 GWh

than 110 MW, as expected from the increased electricity needs throughout the touristic period. On the other hand, lower active power is recorded during November, March, and April, with a median below 55 MW. Over the year, the mean power is 82.7 MW, as shown in Table I, whereas a peak of 227.1 MW was recorded on July 26, 2023, attributed to a malfunction and the subsequent disconnection of two synchronous machines of a power station in the Chania region. Except for a time period of 4 h on that day, i.e., the upper outliers in Fig. 3, it is seen that the active power is restrained below 180 MW throughout the examined period.

A similar trend is observed in Fig. 4 showing the active power losses which are calculated as the difference between the active power measured at the two ends of the interconnection. The losses lie between 2.5 and 9 MW for all the examined months, except for the outlier values recorded on July 26, 2023 that reach 12.2 MW and are related to the peak power flowing through the interconnection at that time. As shown in Table I, throughout the year of analysis, the losses present a mean value of 5.6 MW.

The annual energy transferred through the interconnection per substation is summarized in Table II, along with the energy losses. A total of 710 GWh is sent to Crete from the Hellenic mainland power system through the interconnection, which corresponds to a 22.5% of the total annual demand of Crete. A noticeably lower amount of energy is transferred from the Crete power system towards to the mainland, merely 2% of the total energy injected from either sending end (724.8 GWh). The annual transfer losses sum up to 48.9 GWh, accounting for a 6.75% of the total energy injected to the interconnection.

The active energy recorded at the sending end is distributed

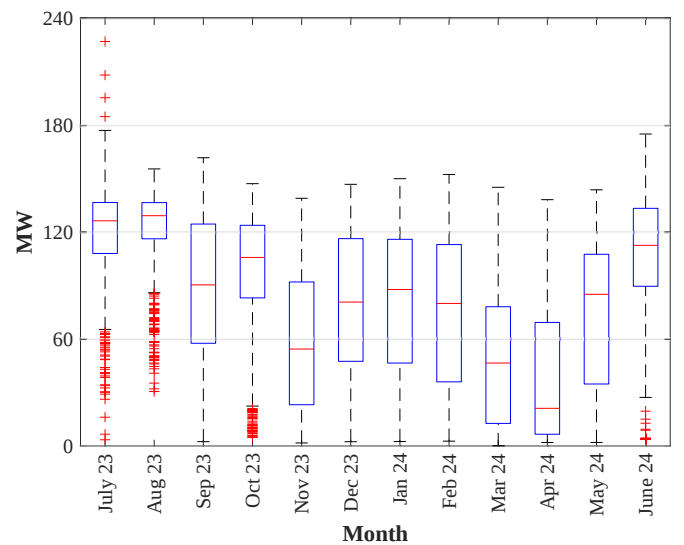


Fig. 3. Active power values as recorded at the sending end.

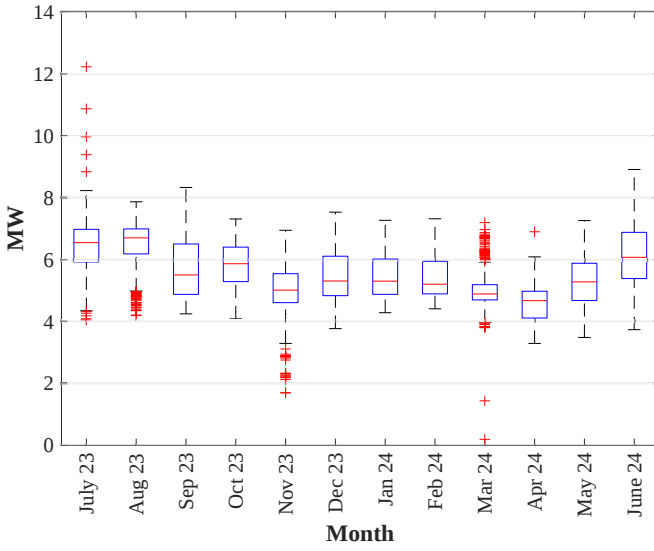


Fig. 4. Cable losses in MW.

TABLE III
MONTHLY ENERGY LOSSES AS A FRACTION OF THE ENERGY SENT THROUGH THE INTERCONNECTION.

2023	July 5.4%	Aug 5.3%	Sept 6.4%	Oct 6.0%	Nov 8.5%	Dec 6.9%
2024	Jan 6.7%	Feb 7.3%	Mar 10.1%	Apr 12.5%	May 7.1%	June 5.6%

throughout the year, as shown in Fig. 5. From the graph it is evident that higher amounts of energy are carried during the summer months, with a maximum of 90.7 GWh observed in August 2023, and a minimum of 26.6 GWh in April 2024. Note that the energy losses vary throughout the year in accordance to the energy transferred. The monthly losses range between 5.3%–8.5% for the majority of the months, as shown in Table III, except for March and April 2024 that are calculated at 10.1% and 12.5%, respectively. Despite these higher percentages, the actual energy losses are low during these two months.

A more detailed analysis for a single-day period is presented hereafter, exploiting 1-min resolution measurements from two representative days: January 10, 2024 (winter) and

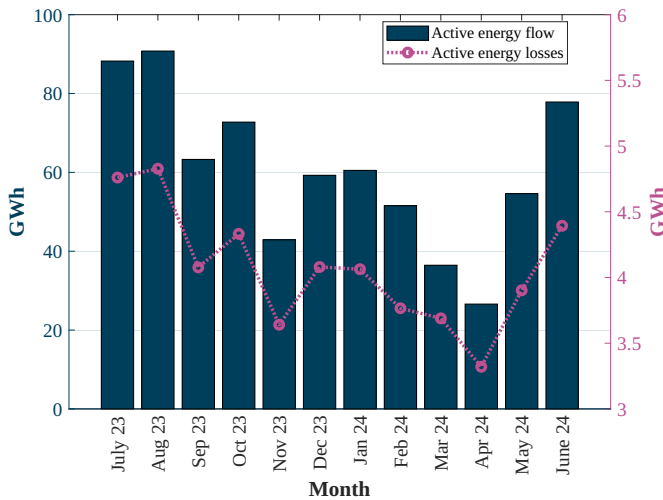


Fig. 5. Active energy flow and losses through the interconnection per month.

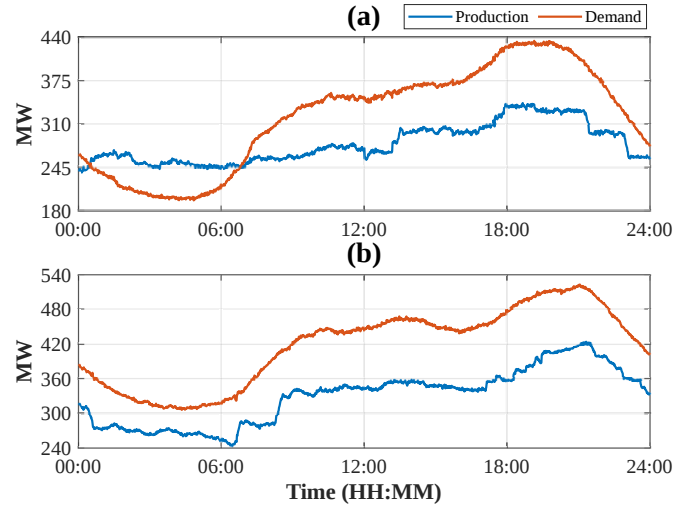


Fig. 6. Power profiles of the total electricity production and demand for the representative (a) winter and (b) summer day in Crete.

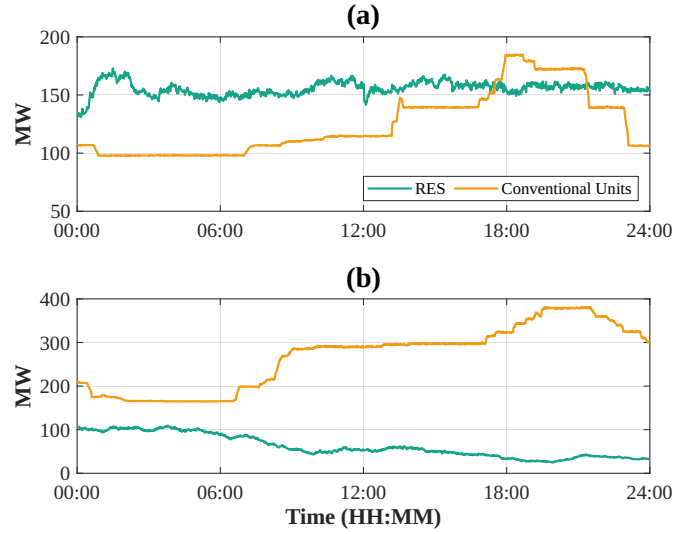


Fig. 7. Electricity production from RES and conventional units on the representative (a) winter and (b) summer day in Crete.

June 10, 2024 (summer). A comparison between electricity, demand, and production is provided in Fig. 6, considering both conventional dispatch units and RES of the Crete island. The latter are discretely presented in Fig. 7. It should be clarified that RES production is calculated as the total generation from all wind parks with a capacity greater than 0.5 MW. While IPTO does not have direct access to generation profiles from other RES units connected to the distribution grid (e.g., photovoltaics), their contribution has been indirectly accounted for in the analysis, since the demand recorded at each substation across Crete actually reflects the net load, i.e., the demand as it appears reduced from IPTO's perspective due to local RES generation at the distribution level.

On the winter day, energy is sent to S/P from S/C during the night hours (production exceeds demand) when the load drops below 247 MW, as illustrated in Fig. 6a; throughout the day, the demand power varies between 195 and 435 MW. During the summer day, as illustrated in Fig. 6b, the load power lies between 305 and 523 MW, always exceeding production, with energy drawn from Peloponnese throughout the entire day.

To delve deeper into the evaluation of active power flow

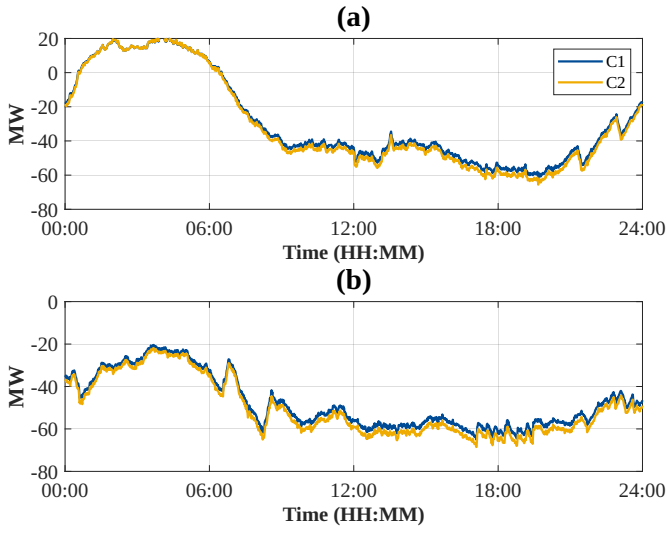


Fig. 8. Active power levels at the S/C terminal of the two cables for a representative (a) winter and (b) summer day. A minus sign indicates active power flowing toward Crete, while a plus sign signifies flow in the opposite direction.

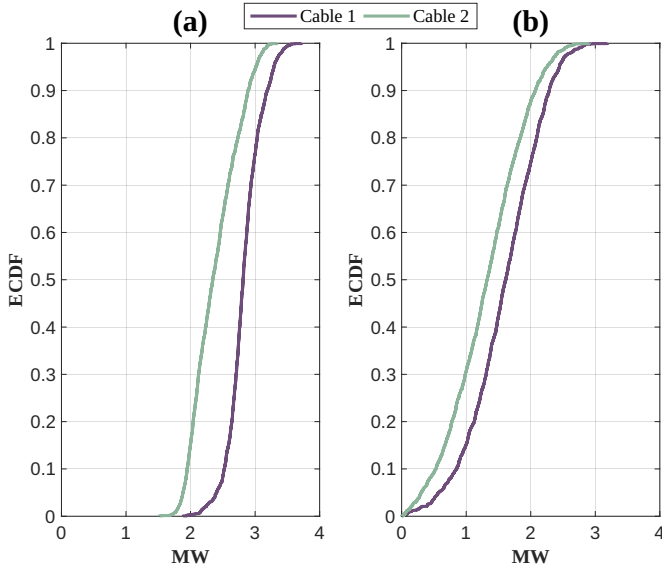


Fig. 9. Empirical cumulative distribution function (ECDF) of active power losses per interconnection cable: (a) winter and (b) summer representative day.

through the interconnection, Fig. 8 illustrates the active power levels at the S/C terminal (points C1 and C2) for the two days examined. Fig. 8a verifies that energy is sent from S/C to S/P during the night hours, approximately 00:00-06:00, while the rest of the winter day a higher amount of energy is sent to Crete to cover the electricity demand. Regarding the summer day depicted in Fig. 8b, the increase of power flow toward Crete demonstrates the energy needed and absorbed from S/P to cover the simultaneous increase in load and decrease of RES production observed in the period 09:00-21:00. Moreover, it is evident that the distribution of power is nearly balanced between the two cables, with a median percentage difference of 4.62% and 4.73% on the winter and summer day, respectively. This unbalance occurs due to the slightly dissimilar length and routing of the cables, which result in different impedance between the conductors.

Finally, Fig. 9 illustrates the power losses along the two cables. The losses mainly lie in the range 2–3 MW for the

longest part of the winter day, and between 1–2 MW during the summer day.

V. CONCLUSIONS

This study focuses on the Crete–Peloponnese submarine/underground ac cable interconnection, with the primary objective of assessing its active power losses over a one-year period. To this end, a detailed description of the interconnection is provided aiming to identify all its operational challenges. In a second stage, real-world active power measurements at both terminals of the interconnection are collected and systematically analyzed.

From the analysis, it is evident that active energy losses are higher during the summer months. This coincides with increased active power flow, which is attributed to the higher electricity demand during the tourist season. Notably, a significant portion of Crete’s electricity—approximately 22.5% of its total annual demand during the one-year period examined—is supplied from the Hellenic mainland via the interconnection. The results show that cable losses remain relatively low, accounting for approximately 6.75% of the total energy injected into the interconnection. The analysis also verifies the capability of the interconnection to secure Crete’s energy supply in the event of a local power generation unit loss. Finally, only a slight discrepancy in power distribution between the two cables is observed, attributed to their marginally different lengths and routing. Future work could focus on comparing active power losses derived from real-world measurements with those calculated using theoretical approaches, while also evaluating the upcoming Crete–Attica HVDC interconnection.

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