Optimized Technique for Maximizing Efficiency in GW-Scale EHVAC Offshore Wind Farm Connections through Voltage and Reactive Power Control

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Abstract

An algorithm based on power flow principles has been devised to enhance generator voltage settings and compensation parameters, thus maintaining equilibrium in current magnitudes across distinct cable lines (CLs). The proposed operational framework is designed to reduce Joule losses while concurrently enhancing the efficiency of cable lines. Moreover, it adheres to network code stipulations regarding reactive power exchanges with the overarching bulk power system. The operational effectiveness of the framework is showcased through a theoretical exploration of a 199 km, 400 kV-50 Hz cable system, which can aggregate up to 2 GW from multiple offshore wind power plants. The data demonstrates that the proposed approach consistently reaches a transmission efficiency of at least 97% in maximum load situations, with generator power factors tending towards unity. The methodology employs variable shunt compensation to dynamically respond to fluctuations in load and enhance voltage stability throughout the system. Furthermore, the methodology demonstrates a high degree of flexibility, accommodating the dynamic nature of renewable energy integration scenarios while ensuring compliance with contemporary grid standards. However, the analysis reveals a potential obstacle associated with the increase in sending-end voltage during full load conditions, thereby highlighting the imperative for comprehensive voltage management protocols at the network connection point. Further research could examine real-world applications to validate the theoretical conclusions and assess the scalability of the framework within diverse working environments.

Keywords: EHVAC, gigawatt-capacity, Efficiency, cross- linked polyethylene (XLPE), Voltage

I. Introduction

The addition of gigawatt-capacity (GW) extra-high- voltage alternating current (EHVAC) offshore wind projects to the power system requires detailed voltage regulation and reactive power handling to boost energy effectiveness and secure grid steadiness. These extensive systems encounter considerable challenges due to the inherently intermittent characteristics of wind energy, protracted transmission distances, and elevated reactive power demands. To effectively mitigate these challenges, it is imperative to employ advanced strategies and technologies that concentrate on optimizing reactive power compensation and voltage regulation, thereby ensuring stable and efficient operational performance. Adopting these strategies is critical for upholding the stability of power systems, curtailing transmission losses, and augmenting the grid's capability to embrace renewable energy. This is particularly crucial considering the growing dependence on offshore wind energy to fulfill global sustainability objectives. Furthermore, innovative control methodologies, including adaptive shunt compensation and sophisticated power flow optimization, are instrumental in dynamically addressing variations in power injections. These efforts enhance both the stability and efficiency of the energy supply network while also supporting adherence to demanding grid codes, ultimately fostering a more resilient and sustainable energy ecosystem. Maximizing efficiency in GW- scale EHVAC offshore wind farm connections through voltage and reactive power control involves a combination of advanced optimization techniques and strategic equipment deployment. The integration of wind farms into the power grid presents unique challenges due to the variability of wind power and the complexity of reactive power management. Effective solutions require a holistic approach that considers both the technical and operational aspects of the system.

It is a optimization strategy that can handle the complexities introduced by intermittent generation sources like wind farms, ensuring efficient integration into the grid(Coath et al., 2004).

- Model Predictive Control (MPC): This method involves predicting system behavior over a certain horizon and optimizing control actions to maintain voltage stability and desired reactive power exchange (Ahmed, 2015).

A. Equipment and Control Strategies

They provide adequate damping and stabilize wind farms under severe disturbances while maintaining bus voltage and controlling reactive power (Wang & Huang, 2010).

- Static Var Compensator (SVC): SVCs, when located offshore, offer better voltage control and lower cable currents, allowing for longer transmission distances without exceeding cable limits. They are particularly effective in both P-Q and P-V control modes (Jerkø, 2014).
- Coordinated Control: Coordinating reactive power output across wind farm groups and collection substations can improve regional grid voltage levels. This approach treats the wind farm groups as a whole rather than independent units, optimizing reactive power flow and voltage stability (Xu et al., 2013).

B. Reactive Power Compensation

- Submarine Cable Compensation: The large charging power of submarine cables can be managed through high voltage reactors, which mitigate the capacitance effect. Setting the power factor of the wind farm to negative can further enhance this compensation (Wen-chao, 2013).
- Voltage Control at Connection Points: Implementing voltage control at network connection points can address constraints due to voltage rise at full load, ensuring high transmission efficiency and near-unity power factor values (Lauria & Schembari, 2014).

While these techniques and strategies offer significant improvements in efficiency and stability, challenges remain in the integration of offshore wind farms. The variability of wind speeds and power production can complicate operations, necessitating robust prediction and control methods to meet grid code requirements(Jerkø, 2014). Additionally, the interaction between different control devices, such as tap-changing transformers and SVCs, requires careful coordination to prevent instability(Opila et al., 2010).

Although these techniques provide substantial solutions for the oversight of voltage and reactive power, significant impediments continue to exist concerning their scalability and integration with the established grid structure. The rising complexity associated with the integration of multiple control systems and technologies across offshore wind farms (OWFs) requires sustained research and innovation initiatives. This initiative is critical to ensure coherent integration and reach maximum performance, particularly as offshore wind energy continues to advance. The persistent growth in the size and functionality of wind turbines, as evidenced by the recent commissioning of 8 MW units, is driving individual offshore wind farms toward achieving gigawatt-scale generation. The locational characteristics of many offshore wind farms (OWFs), frequently positioned over 100 kilometers from shore, alongside the considerable amounts of electricity they produce, create a distinct challenge concerning power evacuation and transmission. . While HVDC systems are the prevailing choice for offshore wind farm applications owing to their improved efficiency over long distances, EHVAC systems have also been considered, especially considering the advent of cross-linked polyethylene (XLPE) insulated 400 kV-50 Hz submarine cables. These high- performance cables deliver remarkable enhancements in both financial aspects and functional capabilities, especially when juxtaposed with conventional copper conductor cables. The implementation of three-core cables equipped with aluminum conductors, for instance, decreases both costs and weight, thereby positioning them as a plausible alternative to copper cables that are capable of handling transmission capacities up to 1 GW per circuit line. This manuscript focuses on identifying the optimal nodal voltage setpoints and dynamic compensation parameters specifically configured for the operational conditions of offshore wind farms. Concurrently, it complies with the network regulations governing the exchange of reactive power at the interconnection point with the grid. In this framework, we introduce a slightly revised power flow algorithm in Section 2. Following this, in Section 3, we conduct an implementation and thorough evaluation of its effectiveness within a test environment, thereby showcasing the promise of this methodology in confronting the operational hurdles related to extensive offshore wind integration.

II. Literature

[1] The paper explores particle swarm optimization (PSO) for reactive power and voltage control in power systems, particularly focusing on integrating wind farms, which can enhance efficiency in managing GW-scale EHVAC offshore wind farm connections amidst intermittent generation challenges.[2] The paper discusses optimizing voltage and reactive power control in wind farms, addressing reactive power limitations, stability of control interactions, and integrated high-level control systems, ultimately enhancing efficiency in large-scale offshore wind farm connections through advanced control algorithms.[3] The paper focuses on using a STATCOM for reactive power-voltage control and damping improvement in a large-scale wind farm, enhancing stability and maintaining bus voltage, which indirectly contributes to maximizing efficiency in wind farm connections.[4] The paper proposes a coordinated control method for voltage and reactive power in wind farm groups, optimizing regional voltage levels and enhancing reactive power distribution, which can improve efficiency in large-scale wind farm connections, though it specifically addresses onshore systems.[5] The paper presents improved modeling and analysis of reactive power management in DFIG-based offshore wind farms, focusing on voltage control and reactive power compensation to optimize efficiency in grid connections through HVAC transmission systems.[6] The paper presents a power flow-based algorithm for optimizing generator voltage setpoints and variable shunt compensation, achieving over 97% transmission efficiency in a 199 km, 400 kV EHVAC system, while ensuring compliance with reactive power exchange constraints.[7] The paper identifies using a static var compensator (SVC) offshore as the optimal technique for maximizing efficiency in GW-scale HVAC offshore wind farm connections, enhancing voltage control and reducing cable currents, thus minimizing active power losses and improving overall system performance.[8] The paper presents an online optimization based fast model predictive control scheme for reactive power and voltage control in grid-connected wind farms, enhancing efficiency by managing reactive power output and voltage set-points to

maintain safety limits and desired exchanges.[9] The paper demonstrates that adjusting cable operating voltage based on wind farm power production can significantly reduce losses in long HVAC connections, achieving up to 21% loss reduction with appropriate voltage regulation, enhancing efficiency in offshore wind farm connections.[10] The paper presents a dedicated algorithm for controlling voltage and reactive power profiles in EHVAC interconnectors, demonstrating its effectiveness in optimizing operations for GW-sized offshore wind farms, with results closely matching those from standard OPF software in various scenarios.[11] The paper presents a reactive power control method for wind farm clusters, focusing on voltage management through local, coordinated, and emergency control modes, optimizing grid-connection point voltage to enhance efficiency in offshore wind farm connections.[12] The paper presents an optimal reactive power management strategy for transmission-connected grids with wind farms, focusing on minimizing reactive power exchange and maintaining voltage profiles, which can enhance efficiency in large-scale offshore wind farm connections.[13] The paper presents a coordinated reactive power control strategy for HVDC-connected offshore wind power plants, optimizing reactive power references to minimize active power losses in the offshore AC grid, thereby enhancing efficiency in large-scale offshore wind farm connections.[14] The paper presents a method for real-time control of reactive power voltage in wind farms, enhancing grid stability and acceptance capacity by utilizing multi-reactive power source interactions, thereby optimizing efficiency in large- scale wind power connections.[15] The paper presents a coordination control method for reactive voltage in wind farms, optimizing reactive output through a model that integrates double-fed induction generators and SVCs, enhancing local voltage levels and maximizing reactive margins using an improved chaos ant colony optimization algorithm.

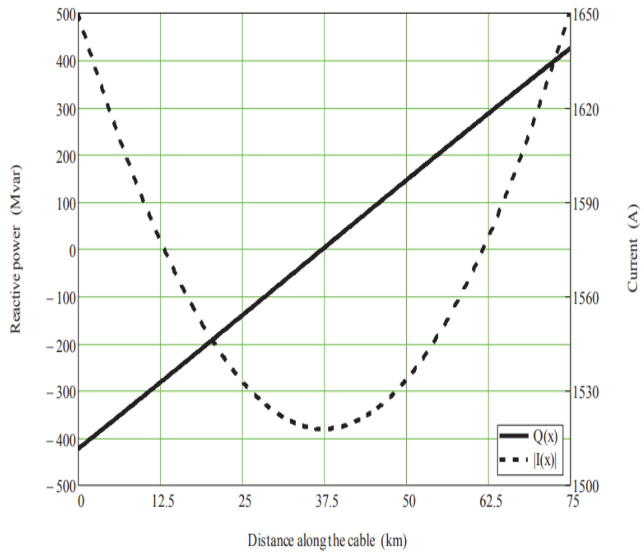
III. METHODOLOGIES

3.1. Optimal Functionality of an Alternating Current(AC) Cable Interconnector:

a. General considerations:

The operational capacity of cable lines is chiefly limited by their ampacity, which, within the framework of practical Extra High Voltage Alternating Current (EHVAC) systems, is persistently less than the current magnitude linked to surge impedance loading. EHVAC cable lines display considerable reactive power generation under various operating conditions. The charging current associated with the system lessens the effective capacity for active power transmission and contributes to an uneven distribution of current along the cable, with maximum current levels observed at the terminals. The optimization of active power transmission efficiency in a consistent cable line necessitates the establishment of a symmetrical current magnitude distribution. This condition is realized when the current levels at both cable terminals are uniform, ensuring that maximum active power transmission occurs while both terminals adhere to their respective ampacity limitations. Achieving the requisite current characteristics, particularly in contexts of heightened active loading, requires diligent control of the terminal voltages. Figure 1 depicts the distribution of current magnitude and reactive power along a 75 km, 400 kV-50 Hz cable line operating at maximum load conditions, while Table 1 details the specifications for the cable. This study emphasizes the vital necessity of voltage management strategies in addressing uneven current distribution and enhancing the comprehensive effectiveness of power transmission.

An assessment of Figure 2 suggests that, across all the loading conditions studied, the operational point at which terminal currents are equal closely aligns with the minimum point on the loss curve. This conclusion accentuates that, within a radial cable system, even when made up of several series- connected line segments, a balanced current distribution in each segment promotes near-minimal losses while enhancing the load-bearing capability of the individual segments. This state of operation, designated as the "optimal operational state," signifies the maximum utilization of the system. By preserving this operational state, the radial cable system secures enhanced effectiveness and reliability in the conveyance of active power, thereby promoting both the reduction of losses and the efficient utilization of resources. The equation leading the short-line resistive voltage drop offers a dependable and accurate approximation of the voltage regulation USRU_{SR}USR, thereby facilitating the effective utilization of a uniform cable line (CL), as illustrated in [11]. This technique has been scaled to incorporate inhomogeneous cable lines that do not feature intermediate shunt compensation, achieving terminal current equality solely in the segments of the line that are either under the highest load or exhibit the least robustness. An exemplary application of this methodology can be observed in the 118 km, 245 kV-50 Hz Malta-Sicily interconnections. Proposed enhancements to the methodology pertain to radial systems comprising multiple series-connected segments, which may incorporate intermediate compensation, as noted in [10]. The resultant "optimal" voltage levels serve as control parameters for the regulation of EHV busbar voltages. Even though these iterative algorithms produce exceptionally accurate results, their complexity substantially rises with an increased number of generators or greater variability within the CL segments. To tackle these complexities and offer a comprehensive solution for the analysis of the operational regimes of a radial AC cable system under conditions of "maximum utilization," an extensive framework is introduced. This framework systematically establishes the voltage and reactive power control setpoints, thus assuring effective operation even within the context of complex network configurations and varying load scenarios. As demonstrated in Fig. 1, a significant correlation can be observed between reactive power and current magnitude that alters with length for a 75 km, 400 kV-50 Hz transmission line, referencing cable C3 information. The voltage at the sending end is designated as US=400 kV, while the active power at the receiving end is denoted as PR=1025 MW,

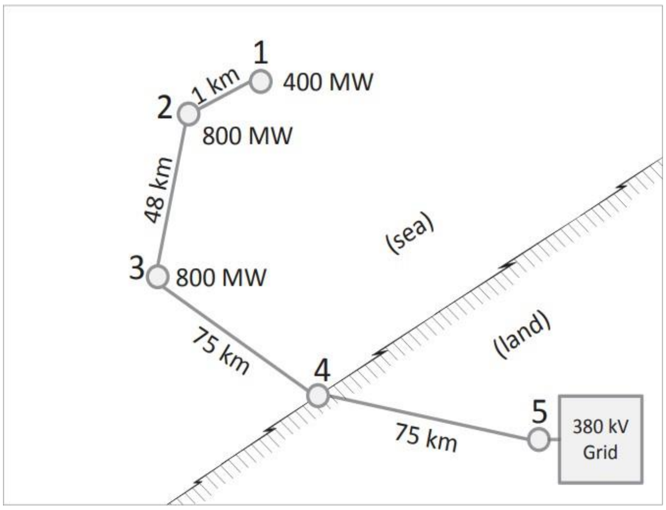


representing the maximum permissible loading of the line.

Fig. 1, a significant correlation can be observed between reactive power and current magnitude that alters with a 75 km, 400 kV-50 Hz transmission line

B. Implementation on the Test System:

The theoretical 400 kV-50 Hz radial interconnector scrutinized in [10] encompasses an aggregate length of 199 km, incorporating 75 km of subterranean infrastructure that extends from the coastal terminus to the inland substation. The structural design of this interconnector seeks to integrate the electrical output from three significant offshore wind farm (OWF) clusters, demonstrating rated capacities of 400 MW, 800 MW, and 800 MW, respectively. The system is structured with nodes 1, 2, and 3, which denote the extra-high voltage (EHV) collection platforms linked to the offshore wind farms. Node 4 is designated as a compensatory station positioned at the interface between marine and terrestrial environments, whereas node 5 represents the network interconnection point. These cables feature three-core submarine cables with aluminum conductors in addition to single-core aluminum cables designed for the terrestrial segment. The proposed system's configuration secures the reliable evacuation of the total rated output of 2 GW from the three offshore wind farms, thereby indicating the feasibility of effectively transmitting large-scale renewable energy through this interconnector. This configuration signifies a crucial stage in facilitating the incorporation of offshore wind energy into the extensive grid, thereby supporting the transition towards more sustainable energy alternatives. generator nodes 1, 2, and 3 are not fixed, a factor that is vital for the adept management of current distribution throughout the three adjacent line segments. The voltages that remain indeterminate are related to the segments situated between nodes 1-2, 2-3, and 3-4.The present distribution along the segment between nodes 4 and 5 is influenced by the modification of the variable shunt compensation at node 4, which serves as a 'load' (P, Q) node. The adjustment in shunt compensation, indicated as ΔQSh4,for the section between nodes 4 and 5. As a result, the management of the power factor at the network connection juncture, facilitated through locally instituted variable shunt compensation. This methodological framework guarantees that the system sustains equilibrium, with voltage and reactive power precisely regulated across all segments, thereby enhancing the management of power flow within the interconnector.



Stretch	Cable[(a)]	Length (km)	P_c (MW)	S_z[(b)] (MVA)	P_{max}[(b)] (MW)	# of circuits
1-2	C1	1	3155	622	622	1
2-3	C1	48	3155	622	589	2
3-4	C2	75	4341	1066	1012	2
4-5	C3	75	3016	1086	1017	2

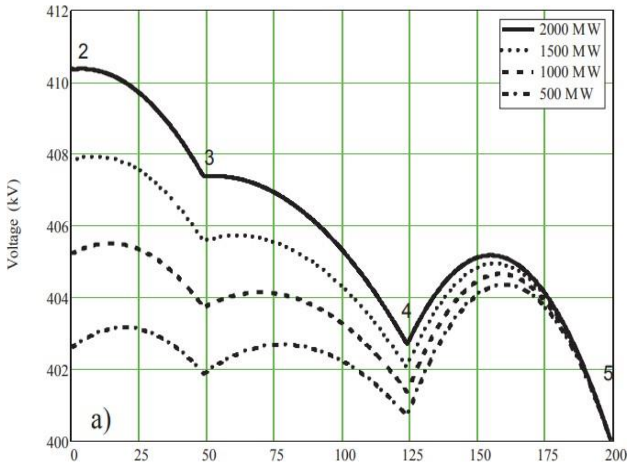
Table 1: Length and transmission capacity of CL stretches

The conceptual diagram in Fig. 2 outlines the experimental framework, concentrating on spatial correlations alongside the performance metrics of the Offshore Wind Farm (OWF).The implementation of the modified power flow analysis for the test system is comparatively uncomplicated. In its fundamental representation, bus 5 is identified as the slack bus, upholding a constant voltage, which effectively reduces the system to a 5-bus radial arrangement. The voltages present at

The conceptual diagram in Fig. 2 outlines the experimental framework, concentrating on spatial correlations alongside the performance metrics of the Offshore Wind Farm (OWF).

I. Results and Discussion

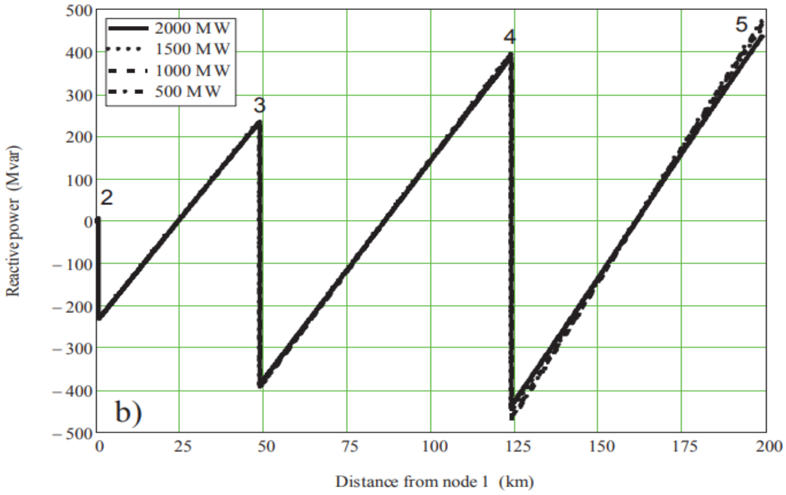
To analyze the effectiveness of the generator voltage and variable reactor setpoints determined by the proposed algorithm, a detailed series of power flow simulations were executed utilizing the simplified system illustrated in Fig. 4. These simulations were systematically developed to investigate how the assigned voltage and compensation adjustments affect the holistic performance of the system, especially in relation to current distribution, voltage regulation, and reactive power management. Through the application of the algorithm in various operational frameworks, the analysis aimed to corroborate its strength and highlight any potential opportunities for refinement in achieving efficient power transmission across the system. The simulations sought to investigate the algorithm's effectiveness in optimizing voltage regulation and reactive power distribution under different operational conditions. Figure 5 demonstrates the findings, illustrating the voltage magnitudes and reactive power flows along the interconnector for varying levels of aggregate offshore wind farm (OWF) output, spanning from 25% to 100% of capacity. These outcomes deliver a definitive portrayal of how the system modifies in response to changes in OWF output, highlighting the algorithm's effectiveness in ensuring stability and efficiency over a broad spectrum of operating scenarios. The investigation confirms that the suggested method maintains uniform voltage characteristics and balanced reactive power dynamics, despite high variability in OWF generation, validating its resilience and suitability for large-scale integration of renewable energy.



(a)

Figure 3: The steady-state operational efficiency realized through the execution of the proposed algorithm, across a range of cumulative Offshore Wind Farm (OWF) output values. a) Voltage and b) reactive power along the interconnector. U5=400 kV.

(b)



(a)

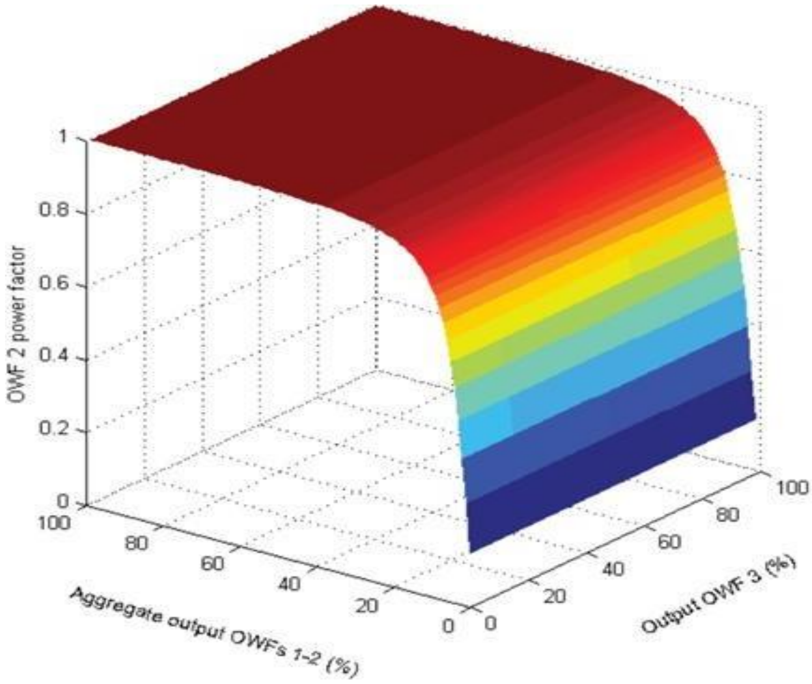
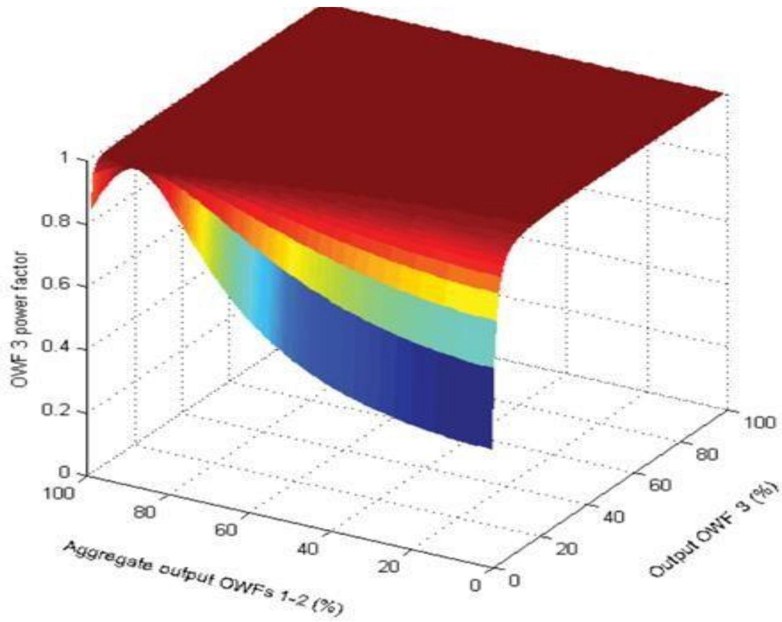


Figure 4: Linkage between the power factor values of the Offshore Wind Farm (OWF) and the active power output. a) Node 2; b) Node 3. The operation at maximum utilization is represented by U5=400 kV.



(b)

Power factor values are observed to be comparatively high across the range of operational scenarios, except during conditions of minimal active power outputs. Under such conditions, the insignificant reactive power excess arising from the compensated cable losses (CLs) becomes comparatively significant, leading to a reduction in p.f. values. Fig.3 Linkage between the power factor values of the Offshore Wind Farm (OWF) and the active power output. a) Node 2; b) Node 3. The operation at maximum utilization is represented by U5=400 kV. At node 2, the power factor is regulated entirely by the local active power injection, thus preserving a more straightforward and predictable pattern. In contrast, the dynamics at node 3 reveal greater complexity, illustrating the effect of additional variables. Fig.4 The steady-state operational efficiency realized through the execution of the proposed algorithm, across a range of cumulative Offshore Wind Farm (OWF) output values. a) Voltage and b) reactive power along the interconnector. U5=400 kV. Yet, even at node 3, diminished power factor values are only perceived under conditions of minimal OWF output. These results highlight the system's ability to effectively manage reactive power and regulate voltage under various operational conditions, with reductions in power factor limited to situations characterized by minimal active power contributions from the Offshore Wind Farms (OWFs).

IV. Conclusion:

This analysis investigates the operational performance of a radial extra-high voltage alternating current (EHVAC) cable transmission system, integrating multiple points of power injection and adjustable shunt compensation mechanisms. An approach based on power flow methodologies was utilized to identify generator voltage setpoints and enhance compensation arrangements, aiming for an equitable current distribution among distinct circuit lines (CLs). The investigation highlights the critical necessity of adhering to network code stipulations concerning steady-state reactive power exchanges within the extensive electrical grid. In order to validate the proposed system, steady-state simulations were conducted on a theoretical cable system of 199 km, functioning at 400 kV-50 Hz, designed to aggregate up to 2 GW from multiple offshore wind farms (OWFs). These simulations validated the effective implementation of the operational conditions, ensuring minimal Joule losses and optimal active power transmission efficiency throughout the cable lines. The reactive power exchanged at extra-high voltage (EHV) generator nodes remained minimal, with power factor values nearing unity under significant load conditions. Voltage elevations in the most remote segment of the interconnector may introduce operational challenges, thereby necessitating effective voltage regulation to mitigate such complications. Subsequent research endeavors could emphasize the enhancement of control mechanisms to improve functionality during periods of diminished output and broadening the system's scalability to support even more extensive offshore wind farm capacities. To summarize, the proposed system reveals significant potential for the incorporation of large-scale offshore wind farm outputs into the electrical grid while upholding high transmission efficiency and conformity to network standards. Future studies could aim to enhance regulatory frameworks to improve efficiency in low-output phases and extend the system's scalability to accommodate more substantial offshore wind energy developments.

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