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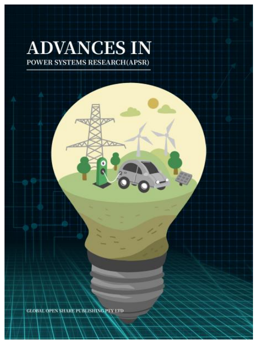

Article

Modular Multilevel Converter Based Reactive Power Compensation for Offshore Wind Farm Using HVAC Transmission System in MATLAB Environment

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Abstract

Offshore wind farms (OWF) have received a lot of interest as a possible source of renewable energy (RE). However, due to the considerable distance from the coast, their gearbox systems encounter major obstacles, resulting in substantial losses and voltage drops. In high-voltage alternating current (HVAC) transmission systems (TS), reactive power compensation (RPC) is critical for voltage stability and efficient energy transfer. The goal of this research is to create the best reactive power adjustment approach for OWFs HVAC TS by 36 power module modular multilevel converter (MMC) techniques. To establish the best level of RPC, the proposed technique takes into account a number of elements, including reactive power demand, voltage stability, and losses. The study employs simulation tools such as MATLAB Simulink to analyze and evaluate the performance of the proposed strategy. The results show that the proposed technique can greatly improve voltage stability and reduce losses in OWFs HVAC TS.

Keywords

Optimal reactive power compensation, High voltage alternating current (HVAC) transmission system, Offshore wind farms, Onshore electric grid

Article History

Received: 25 January 2025
Revised: 2 March 2025
Accepted: 14 March 2025
Available Online: 14 March 2025

1. Introduction

Offshore wind farms (OWFs) are becoming an essential part of the energy mix because of their capacity to capture high and steady wind speeds, but integrating offshore wind power into the onshore grid poses a number of technical challenges, such as reactive power compensation, voltage stability, and power quality. The growing demand for renewable energy worldwide has resulted in notable advancements in offshore wind power generation [1]. One of the primary issues in the high-voltage alternating current (HVAC) transmission of offshore wind energy is the excessive reactive power generation due to long submarine cables [2]. This reactive power must be managed effectively to maintain stable grid operation and ensure efficient power transfer. In HVAC transmission systems, modular multilevel converters (MMCs) have become a promising solution for reactive power compensation [3]. MMCs are well suited for offshore wind applications due to their high efficiency, scalability, and superior harmonic performance. By using an MMC-based reactive power compensation scheme, the system can dynamically adjust the reactive power flow, improving voltage stability and reducing power losses. Additionally, the MMC technology allows for flexible AC transmission system (FACTS) functionalities, which improve grid reliability and integrate renewable energy sources [4].

Transporting electric power from generators to loads is one of an electric power system's primary tasks. The voltage must be maintained across the entire power system within an acceptable bandwidth (often 5-10%) in order for it to operate as intended [5,6]. Offshore wind energy production has increased significantly in recent years, particularly in Europe [7,8]. Based on effective, dependable, and affordable designs, a number of transmission system (TS) configurations have been suggested to integrate big offshore wind power plant (OWPP) to shore [9]. For offshore transmission systems, HVAC and HVDC configurations are being studied [10]. Long distances are typically covered by HVDC systems since no reactive power is produced and power loss costs can be lower than with HVAC solutions [11]. The use of mid cable reactive power correction and recently created AC cables with greater voltages are currently being studied for HVAC systems over longer distances [12]. Wind energy is becoming increasingly important around the world. This rapid development of wind energy technology and the market has significant implications for a variety of people and institutions, including scientists who research and teach future wind power, electrical engineers at universities, and professionals at electric utilities who must understand the complexities of the positive and negative effects that wind energy can have on the power system [13]. Currently, five countries Germany, the United States, Denmark, India, and Spain account for more than 83% of global wind energy capacity [14]. The majority of the expertise linked to wind energy development and integration into those countries' power systems here [15]. Wind energy has been used for nearly 3000 years, and the technology has gotten highly complicated [16]. Aerodynamics, structural dynamics, mechanical engineering, and electrical engineering are all involved [17].

A variety of TS topologies based on efficient, dependable, and cost-effective designs have been proposed to link big OWPP to shore [10]. Offshore gearbox systems are currently being investigated in HVAC and HVDC configurations [18]. HVDC systems have traditionally been employed over long distances since no reactive power is generated and power loss costs can be decreased when compared to HVAC solutions [7]. HVAC transmission systems are chosen for usage in OWPP located within 40 kilometers of the shore line [19]. OWF produce energy at a distance from the land; the transmission of this energy depends greatly on the offshore wind farm's power rating and its distance from the nearest onshore grid link. Figure 1 displays both AC and DC transmission options [20]. The technology used in HVAC transmission is straightforward yet quite sophisticated. Transformers, AC wires, and reactive compensation components would make up the full transmission and receiving station apparatus. Since power generation is alternating in nature, the generated voltage level can be raised to the necessary transmission level using a straight forward step-up transformer [21].

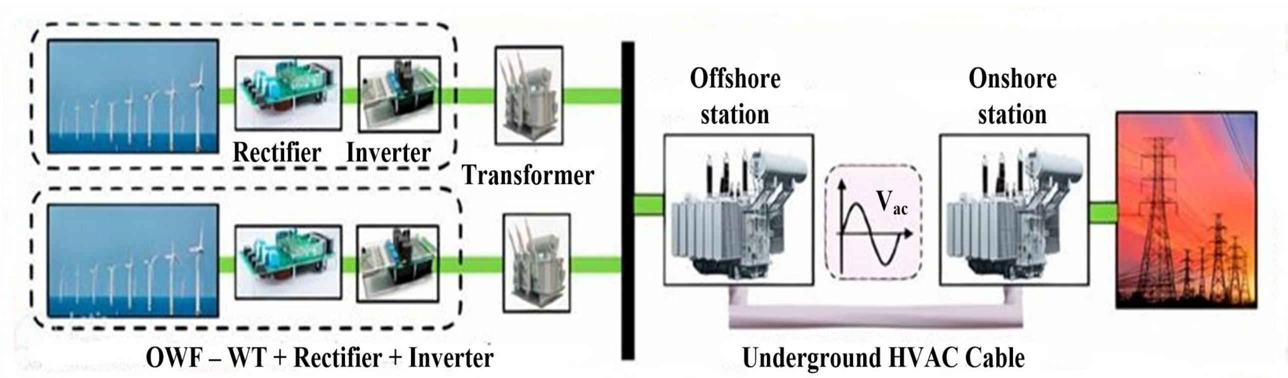

Figure 1. Offshore wind power plant for HVAC transmission system

HVAC cables have a larger capacitance than overhead lines, which should be adequately adjusted. In [22] the P model of three-core XLPE cable, which is commonly utilized in offshore wind power plants, was used. OWPPs already employ XLPE cable extensively in large part because of its excellent insulation and thermal stability capabilities [23].

Due to their unique architecture, three-core armored XLPE cables have a larger capacitance between their layers or between their shell and the seabed than overhead lines [24].

IEC 62586-1 provides standards for the testing and operation of power electronic systems used in high-voltage direct current (HVDC) and alternating current (HVAC) transmission. While the study primarily focuses on MMC for reactive power compensation in HVAC systems for offshore wind farms, the principles and testing methodologies outlined in IEC 62586-1 were considered to ensure that the system adheres to the relevant safety, reliability, and performance standards.

The study indirectly references these standards to guide the modeling of system behavior, particularly in terms of voltage regulation, reactive power support, and grid integration. Although the specific requirements of IEC 62586-1 are more tailored to HVDC systems, the underlying methodologies for power system stability, fault handling, and performance evaluation are applicable to the MMC-based system we are studying. The MATLAB simulations incorporate various fault scenarios and operational conditions that align with the framework set by IEC 62586-1, ensuring that the reactive power compensation system performs reliably and meets the necessary operational standards for offshore wind farms.

1.1 Scope of the Research

In terms of the project's scope, the analysis of the export system and offshore wind farm is the main focus. Owing to its extensive scope, the fundamental components of the system are explained in a fair amount of detail, while components of less significance are either noted or left out. For this project, the electrical models are crucial, and throughout the process, obtaining precise values and forming reasonable assumptions have been top priorities. Power flow equations and constraints are offered in the problem formulation with minimal omissions; nevertheless, cost functions are taken straight from the literature and no explanation of their derivation is given because it is available in the references.

1.2 Objectives of the Research

- To examine various OWPP transmission system topologies in order to identify the best option for each situation under consideration.
- To introduce the 36-Power Module System for compensation of reactive power in HVAC Transmission.
- To show the results acquired by using MATLAB Simulink Software.

1.3 Benefits of Implementing This Approach in Real-World Offshore Wind Farm Operations

Implementing the Modular Multilevel Converter (MMC)-based reactive power compensation system in offshore wind farm operations offers several significant benefits. It enhances voltage stability across the wind farm, ensuring that the system remains reliable and avoids voltage fluctuations during variable wind conditions. Additionally, it improves overall power quality by maintaining a balance between active and reactive power, which helps reduce power losses and prevent issues like voltage or current harmonics. The system also minimizes transmission losses by reducing the need for long-distance reactive power flow, leading to more efficient energy transfer from the offshore wind farm to the onshore grid. Furthermore, the MMC's ability to manage reactive power efficiently improves the operational efficiency of both wind turbines and the HVAC transmission system, ensuring maximum active power is transmitted with minimal disruptions. With faster responses to dynamic load conditions, the system can adjust to changes in real-time, maintaining balance even under rapidly changing generation or consumption. The MMC-based approach also helps ensure compliance with grid codes, particularly in terms of voltage regulation and reactive power support, which is crucial for integrating renewable energy sources into the grid. Moreover, the system's modularity and scalability offer long-term reliability, reduce maintenance costs, and allow for future upgrades or expansion to accommodate more renewable sources. Overall, this approach can lead to improved system reliability, reduced operational costs, and greater economic performance for offshore wind farms by ensuring more effective power transmission and better integration with the grid.

2. Problem Statement

Arrays of WTs connected to one another and positioned in a body of water, typically at sea, make up OWPPs [10]. The arrays are arranged according to precise plans intended to maximize wind and minimize aerodynamic forces between turbines [25]. After passing via cables to an offshore substation (OSS), the energy produced by turbines is transferred to the main grid [26]. Figure 2 shows the internal grid of wind turbines, transformer substation (TS), and underground export line the major components of an OWPP. Furthermore, the internal grid operates at Medium Voltage (MV) and each turbine has its own transformer when the turbines have a big capacity as is frequently the case in offshore facilities. An HV/GV transformer is put onshore in cases when the transmission voltage deviates from the grid voltage.

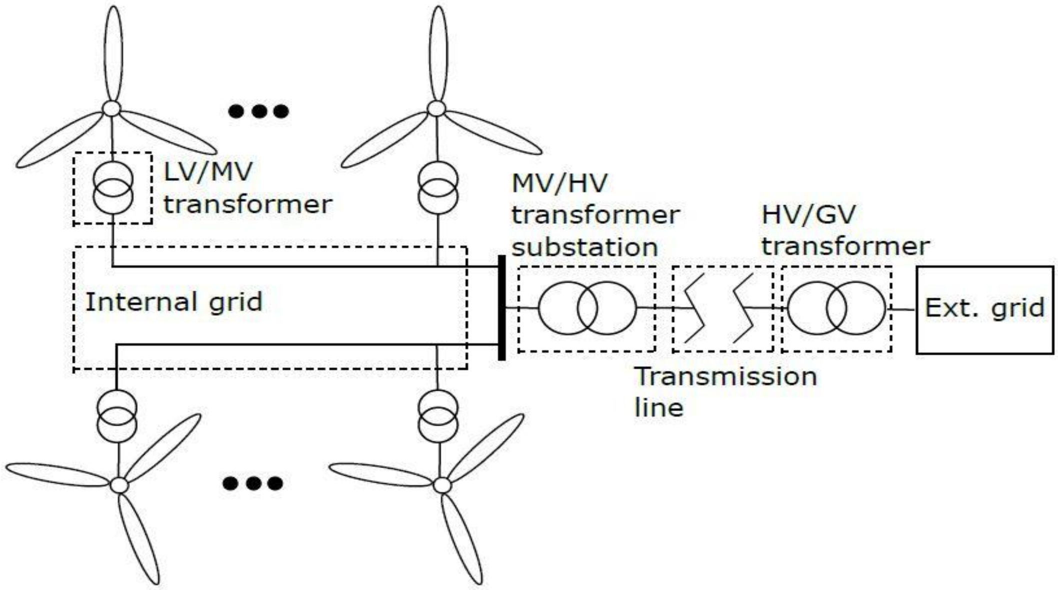

Figure 2. OWF arrangement

Because of their low power production and close proximity to the coast, the earliest OWPP exported electricity using MVAC. On the other hand, the capacity of OWPPs has increased gradually in recent years, and Figure 3 shows the several GW-scale projects that are now being built. Additionally, the sector is expanding farther offshore, which allows for bigger sea areas with more consistent wind patterns, lessens hindrance with other economic endeavors, and lessens the visual impact. However, extending the distance from the shore not only results in increased installation costs, but it also presents a number of technical difficulties for long-distance power transmission.

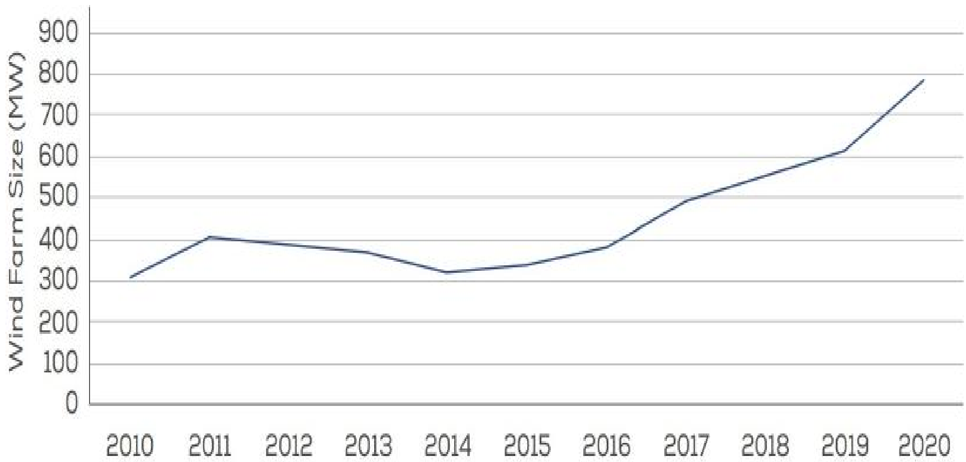

Figure 3. Europe's average WF capacity

The correction of the reactive power generated by the cable is a crucial issue when considering HVAC transmission systems. Grid operators normally require a power factor of one, which means that the system must be capable of avoiding any delivery of reactive power from the grid [6]. Researchers have offered several settings to overcome this issue. Installing shunt reactors (SR) at both ends of the export cable, which can be located on the LV or HV side of transformers, is a typical solution [27]. As previously stated, mid cable reactors can also be constructed for huge facilities located far offshore [9].

3. Proposed Methodology

Step by step methodology is illustrated in Figure 4. In an HVAC gearbox system, a methodology is used to determine the ideal voltage as well as the placement, size, and number of reactors. Several HVAC gearbox layouts based on different voltage levels, U_i , and reactor combinations, C_i , are considered. The power losses and cost of reactors are optimized for each configuration of U_i and C_i , taking into account OWPP operating at various wind speeds [10]. As a consequence, depending on the overall cost of each HVAC gearbox arrangement, the best solution is chosen. In addition, the entire cost of HVAC and HVDC is evaluated to pick the final offshore TS [11].

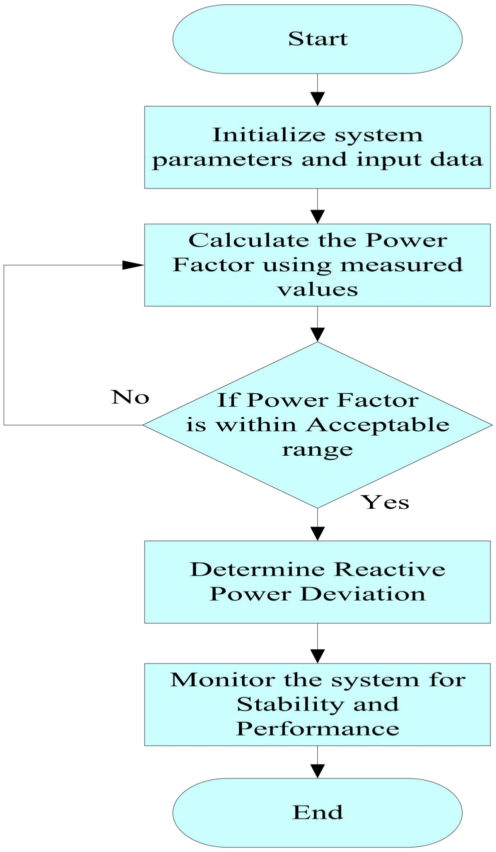

Figure 4. Flowchart for proposed methodology

4. Results & Discussion

It discusses voltage management, PFC, and system stability as they relate to reactive power compensation. It has been discovered that by permitting WT to create RP and taking into consideration the various costs of onshore and offshore reactors, significant cost savings can be gained when the costs of offshore and onshore reactors are considered. Throughout the case studies, an important premise was tested: whether reactive electricity from the transformer and converters could substitute the offshore reactor, lowering overall costs. The additional current passing through the collector and transformer, as discovered, creates higher losses, which outweigh the savings from not constructing the reactor. The optimization method, on the other hand, favored capacitive reactive power generation (CRPG), which improved the level of voltage at the buses, reduced the current passing through the cables and, as a result, the losses. Furthermore, it has been discovered that beyond a given distance, cables reach their maximum current carrying capability and turbines must be decreased. This therefore led in a lower active power production from the WF, which increased the cost of losses. Figure 5 illustrates the MATLAB based model to analysis the modular multilevel converter based RPC for OWF HVAC transmission system.

Furthermore, Figure 5 shows an HVAC-MMC interconnection system that uses Modular Multilevel Converters (MMCs) in a MATLAB/Simulink environment to integrate an offshore wind farm (represented by a 400 kV equivalent AC source) with an HVAC transmission system. The MMC units (Ap, Am, Bp, Bm, Cp, and Cm) act as three-phase converters with 36 power modules per arm, enabling reactive power compensation and ensuring smooth AC-DC conversion. The system also includes filters to reduce harmonics and improve power quality, and a DC circuit on the right represents the DC link for additional transmission. Fault injection blocks also enable testing in various grid disturbance scenarios. In addition to controllers for system regulation, the control panel on the left has monitoring tools for voltage (Vdc), active power (P), and reactive power (Q). This simulation model is crucial for analyzing offshore wind power integration, ensuring voltage stability, reactive power management, and efficient power transfer in high-voltage AC transmission networks.

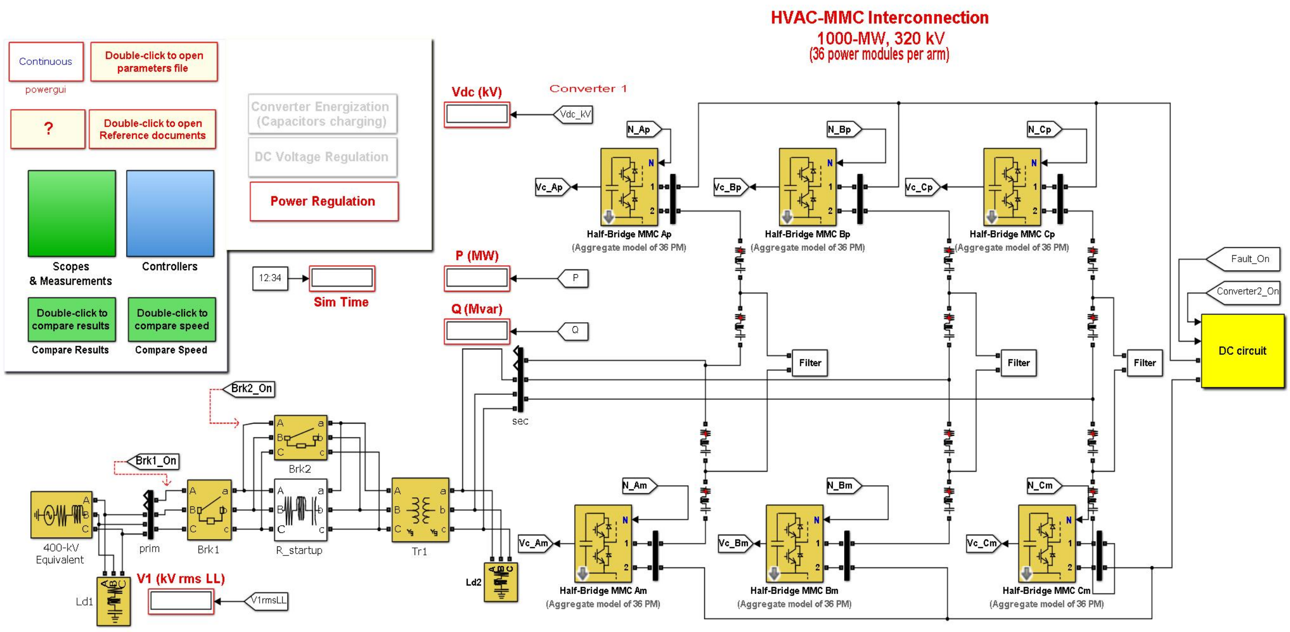

Figure 5. MATLAB simulink model

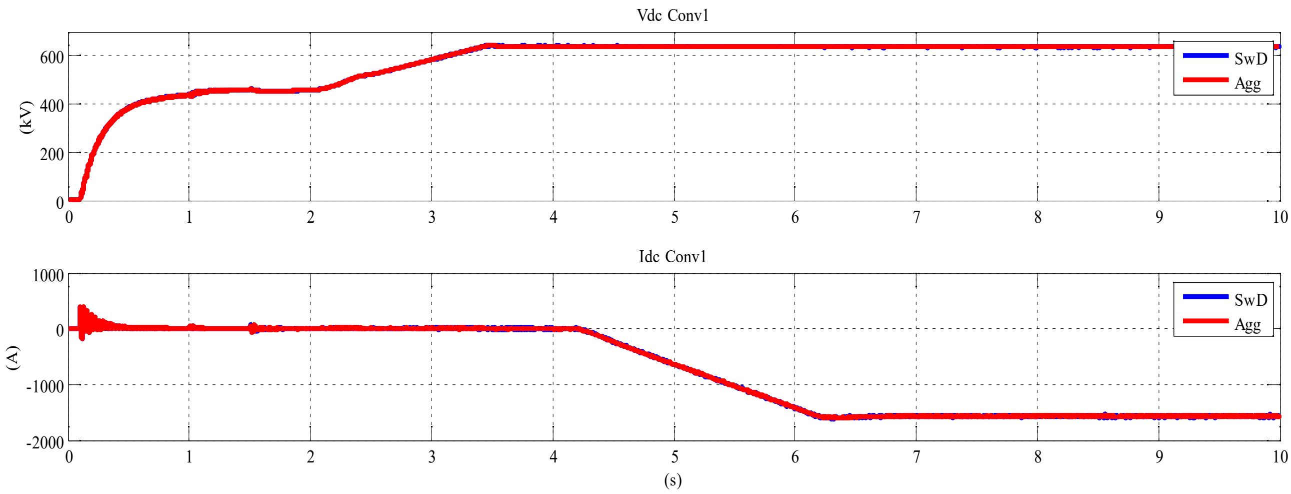

Figure 6. Generated DC voltage & DC current

The upper part of Figure 6 illustrates the relationship between the DC voltage of converter 1 and time, while the lower part of Figure 6 depicts the current of converter 1 with respect to time. The Upper Part Curve showing the increment of DC voltage in kV generated through OWTs up to 3.5 second after that stability occurred and there is no any disturbance (fluctuation) up to 10 second. The lower part of Figure 6 shows the behavior of the generated current in amps through OWFs. There is some disturbance occurring from 0.1 to 0.5 seconds, followed by a period of stable current from 0.7 to 4.2 seconds. After that, the current decreases until 6.2 seconds, and then stabilizes again from 6.2 to 10 seconds.

Furthermore, Figure 6 presents the dynamic response of DC voltage (Vdc) and DC current (Idc) of Converter 1 over a 10-second simulation period in an MMC-based HVAC transmission system. The top plot illustrates the DC voltage (Vdc Conv1), which starts from 0 kV, gradually increases, and stabilizes around 600 kV after approximately 5 seconds, indicating successful DC voltage regulation. The bottom plot represents the DC current (Idc Conv1), which initially exhibits transient oscillations before settling. Around 5 seconds, the current decreases from approximately +1000 A to -1000 A, before stabilizing showcasing the system reactive power compensation and regulation. The presence of two curves (Sw D in blue and Agg in red) suggests different measurement techniques, possibly differentiating between switching dynamics and aggregated values. The smooth rise in voltage and controlled current behavior confirm the effective operation of the Modular Multilevel Converter (MMC), ensuring voltage stability and efficient power transmission in the offshore wind energy system.

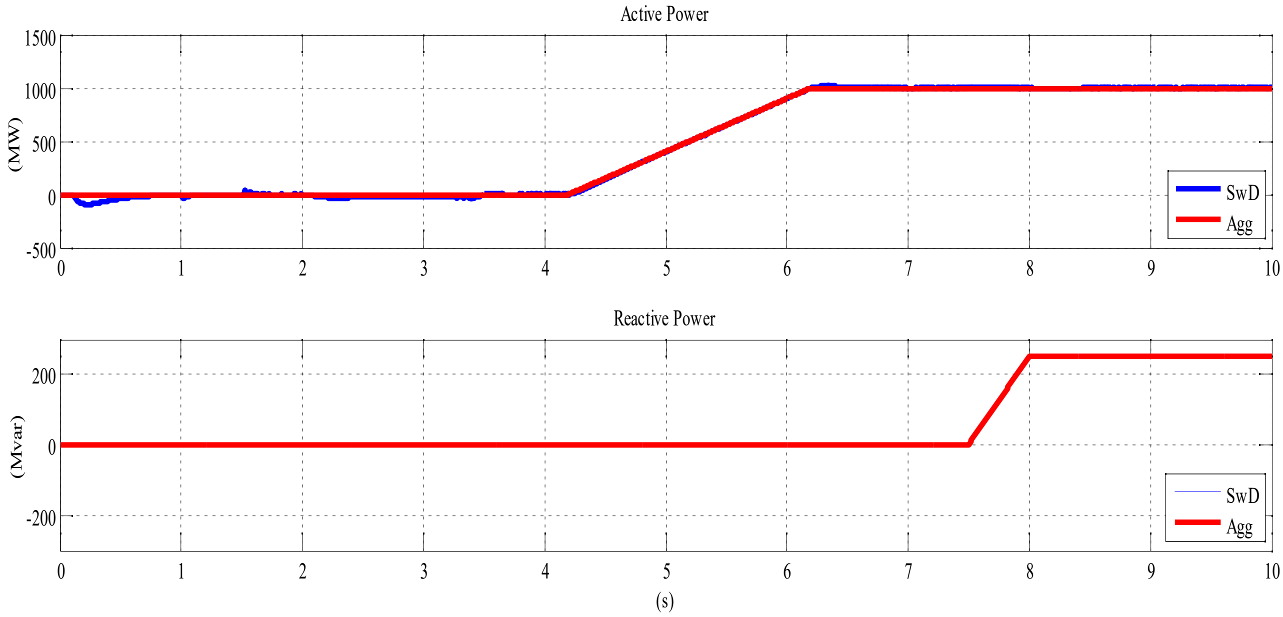

Figure 7. Active power & reactive power

Figure 7 illustrates that the upper part shows the active power increasing from 0 to 1000 MW between 4.3 and 6.2 seconds, after which it remains constant for a period of 10 seconds. In contrast, the reactive power remains at 0 Mvar from 0 to 7.5 seconds, then increases from 0 to 210 Mvar between 7.5 and 8 seconds, and finally remains constant for a period of 10 seconds. The Upper Part Curve showing the Active Power behavior generated through wind turbines along with blue curve line which is showing the distortion created during generation. The Lower Part Curve showing the Reactive Power behavior generated through wind turbines.

Furthermore, Figure7 illustrates the active and reactive power dynamics of an MMC-based HVAC transmission system over a 10-second simulation period. The top plot shows active power (MW), which remains near 0 MW during the initial phase, then gradually increases from 5 seconds onward, reaching approximately 1000 MW by 7 seconds and stabilizing. This indicates a smooth ramp-up in power transfer, ensuring a controlled transition to full-load operation. The bottom plot represents reactive power (MVar), which remains at 0 MVar until around 7 seconds, after which it sharply increases to approximately 200 MVar, signifying the activation of reactive power compensation to maintain grid stability and power factor correction. The presence of two curves (Sw D in blue and Agg in red) suggests different measurement techniques, distinguishing between switching dynamics and aggregated response. The results confirm the effective operation of the MMC, ensuring gradual power stabilization and efficient reactive power management, which are crucial for integrating offshore wind power into the grid.

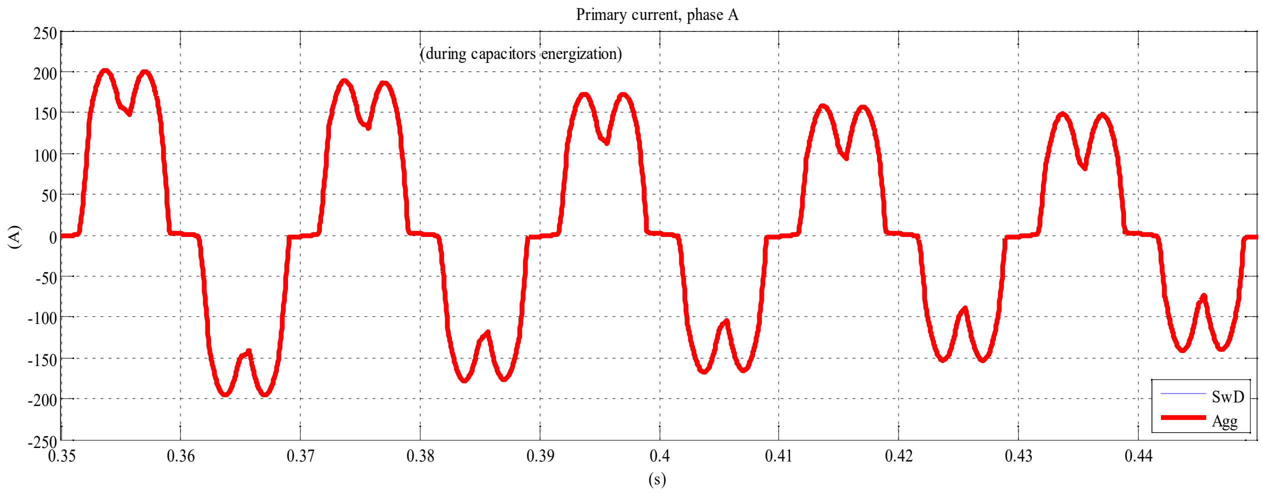

Figure 8. Primary current in phase line 'A'

Figure 8 depicts a curve showing the graph of the primary current behavior in amps flowing through Phase Line A of the transmission. The irregulations showing in curves is due to the energization of capacitors used in 36 Power Modules System for conversion. Figure 9 is illustrated the both upper part and lower part are consists of x-axis (seconds) and y-axis (volts). The Upper Part Curve is split into two parts: Left Side Part is the curve of capacitive voltage of 4 Modules System and Right Side Part is the curve of average capacitive voltage of whole system. The Lower Part Curve is the combination of two Upper Parts showing the average capacitive voltage of upper arm of Phase A.

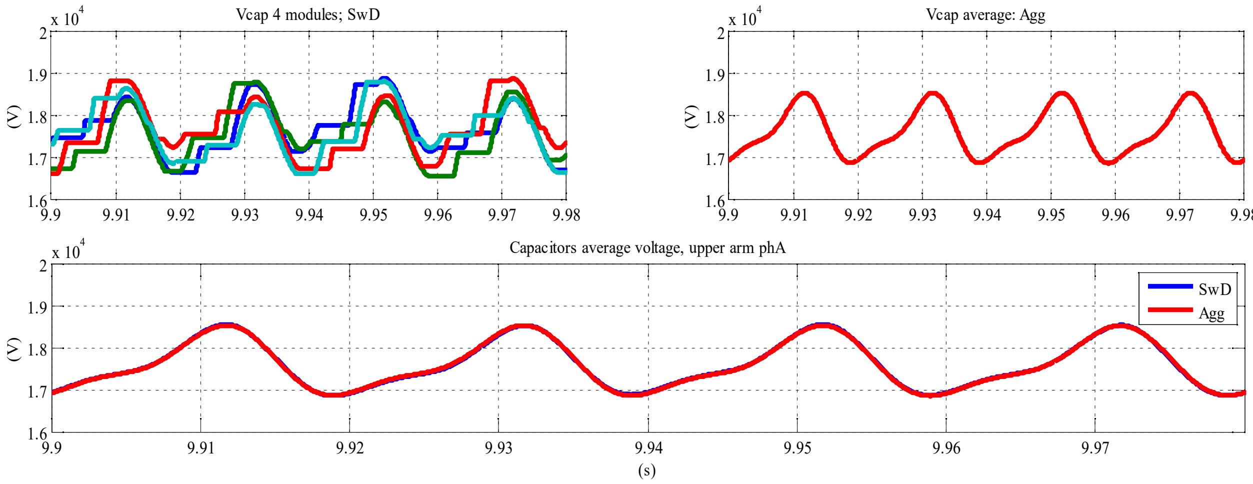

Figure 9. Capacitive voltage

Furthermore, Figure 8 illustrates the primary current waveform of phase A during the capacitor energization process in an MMC-based HVAC transmission system. The x-axis represents time (seconds), and the y-axis represents current (A). The waveform exhibits a distinctive oscillatory pattern with periodic peaks and troughs, indicating the charging dynamics of the converter's submodule capacitors. The current fluctuates between approximately +200 A and -200 A, reflecting the alternating nature of the AC system and the transient response of the MMC during initialization. The label "during capacitors energization" suggests that this waveform occurs in the early phase of system startup when the converter's capacitors are being charged. The presence of two curves (Sw D in blue and Agg in red) implies different measurement techniques, possibly distinguishing between switching-level details and aggregated system response. These oscillations are expected as the capacitors absorb energy to reach their steady-state voltage. The results confirm the correct functioning of the converter, ensuring a stable charging process without excessive inrush current, which is crucial for maintaining system reliability and preventing overloading of the power components.

Figure 9 illustrates the capacitor voltage dynamics in an MMC-based HVAC transmission system, focusing on the voltage behavior of submodule capacitors in the upper arm of phase A. The x-axis represents time (seconds), and the y-axis represents capacitor voltage (V). The top-left plot shows the individual capacitor voltages of four submodules using switching-level data (Sw D), displaying a staircase waveform due to discrete switching events. The top-right plot presents the average capacitor voltage (Agg), which smooths out individual fluctuations, showing a more sinusoidal pattern. The bottom plot further visualizes the overall capacitor average voltage in the upper arm of phase A, demonstrating a well-regulated voltage with controlled oscillations around 1.7×10^4 V to 1.9×10^4 V. The periodic variation in voltage aligns with the expected AC system operation, confirming stable energy balancing within the MMC submodules. The results validate the effective capacitor voltage regulation, ensuring proper power conversion and stable MMC performance in the offshore wind farm's HVAC transmission system.

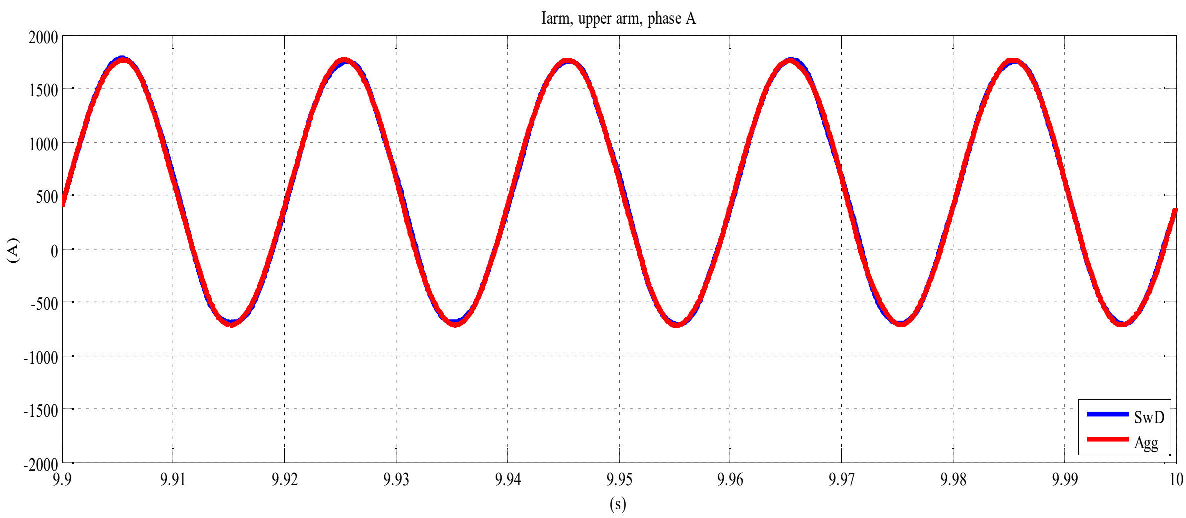

Figure 10. Upper arm current of phase line 'A'

Figure 10 depicts the curve showing the upper arm current of Phase Line ‘A’, with the x-axis representing seconds and the y-axis representing amps. The graph is showing the sinusoidal curve for AC source after conversion from 36 Modules System. The current waveform in the upper arm of phase A is in an MMC-based HVAC transmission system. The x-axis represents time (seconds), and the y-axis represents current (A). The waveform exhibits a smooth sinusoidal pattern, indicating a balanced and stable current flow within the converter’s arm. The current oscillates between +2000 A and -2000 A, consistent with the expected behavior of the modular multilevel converter (MMC) under steady-state conditions. The two curves, Sw D (blue) and Agg (red), closely overlap, suggesting that the aggregated response (Agg) effectively represents the switching dynamics (Sw D) with minimal deviation. This confirms that the MMC operates efficiently, ensuring controlled current flow through its submodules. The results validate the proper functioning of the MMC, with stable upper-arm currents supporting effective AC power transmission, crucial for offshore wind farm integration into the grid.

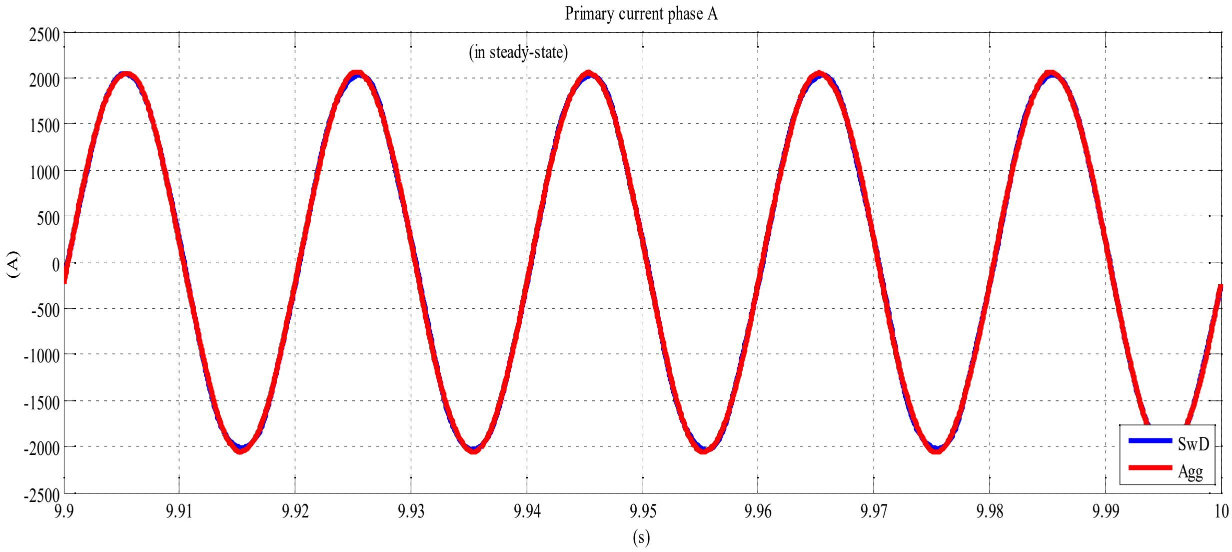

Figure 11. Graph of primary current of phase line ‘A’

Figure 11 illustrates the curve showing the primary current of Phase Line ‘A’, with the x-axis representing seconds and the y-axis representing amps. The graph is showing the sinusoidal curve for HVAC transmission from Offshore Wind Farms to Onshore Electrical Grid. The current waveform is in the upper arm of phase A in an MMC-based HVAC transmission system. The x-axis represents time (seconds), and the y-axis represents current (A). The waveform exhibits a smooth sinusoidal pattern, indicating a balanced and stable current flow within the converter’s arm. The current oscillates between +2000 A and -2000 A, consistent with the expected behavior of the modular multilevel converter (MMC) under steady-state conditions. The two curves, Sw D (blue) and Agg (red), closely overlap, suggesting that the aggregated response (Agg) effectively represents the switching dynamics (Sw D) with minimal deviation. This confirms that the MMC operates efficiently, ensuring controlled current flow through its submodules. The results validate the proper functioning of the MMC, with stable upper-arm currents supporting effective AC power transmission, crucial for offshore wind farm integration into the grid.

Losses Comparison (Before & After): By using a low switching frequency per cell, the IGBT switching losses are significantly reduced compared to a 2-level converter, as are the harmonic losses in the reactors. Furthermore, the conduction losses are reduced through use of Cascaded Two Level (CTL) technology. The total converter station losses are in the range of 1%, as shown in Figure 12.

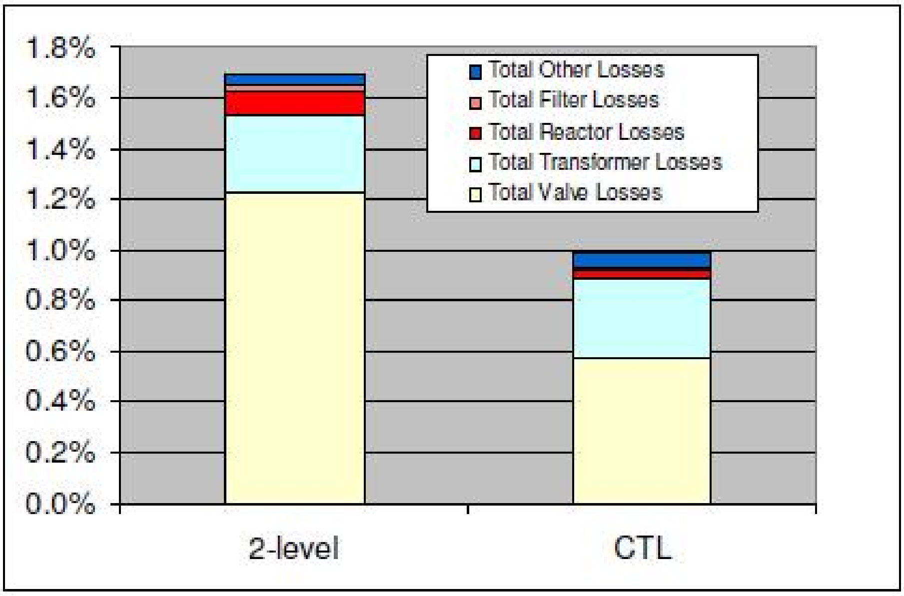

Figure 12. Vertical bar graph for comparison of losses before technique & after using technique

5. Advantages and Key Challenges of Using Matlab for Simulating MMC-Based RPC System

MATLAB offers several advantages for simulating the MMC-based reactive power compensation system, including its powerful Simulink environment for modeling complex power electronics, built-in toolboxes for control system design, and efficient numerical solvers for accurate system analysis. It enables rapid prototyping, real-time simulation, and detailed performance evaluation, making it a preferred choice for studying MMC behavior in reactive power compensation applications.

Key challenges in integrating MMCs into offshore wind farm systems include managing high installation and maintenance costs, ensuring reliable operation in harsh marine environments, addressing complex control and protection requirements, and mitigating harmonic distortions. Additionally, optimizing the coordination between MMCs and wind farm grid dynamics is crucial for stable and efficient power transmission.

6. Conclusion

The function of a mid-cable reactor in an HVAC offshore gearbox system for OWPP is thoroughly examined in this study. The practical distance between HVAC and HVDC transmission systems can be increased and total costs can be decreased by implementing a mid-cable reactor. As a result, an HVAC gearbox system design technique is provided, taking into account certain OWPP rated powers and shore distances. The results indicate that for large OWPP rated powers and distances between 70 and 150 km, using three reactors — including a mid-cable reactor — is a feasible option. However, the cost reduction of HVAC cables and converters, as well as factors in the cost of energy and OWPP lifetime, can modify the break-even distance by tenths of kilometers. It was discovered through thorough calculations and data analysis that the reactive power demand of offshore wind farms can have a considerable impact on system performance, including voltage aberrations and power losses. The study underlined the necessity for effective reactive power compensation approaches to alleviate these difficulties and increase overall gearbox system reliability.

The study also emphasized the need of modern optimization algorithms, such as Genetic Algorithms and Particle Swarm Optimization, in identifying the best size and positioning of reactive power compensation devices. The reactive power flow was efficiently regulated by optimizing these parameters, resulting in reduced power losses and enhanced voltage stability throughout the offshore wind farm. The recommendations presented can be helpful to power system operators, engineers, and researchers involved in the construction and operation of offshore wind farms. Implementing these tactics can result in improved performance, dependability, and energy efficiency in the context of offshore wind power generating.

Data Availability

Data will be made available on request.

Declarations of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Mohsin Ali Koondhar: Conceptualization, Methodology, Software, Investigation, Formal analysis, Writing – original draft. Asad Rehman: Conceptualization, Data curation, Writing – review & editing. Zafar Ali: Visualization, Formal analysis, Validation and Investigation. Munawar Jamali: Conceptualization, Supervision, Software, Visualization, Investigation. Irfan Ali Channa: Investigation, Data curation, Validation, Resources, Writing – review & editing.

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