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Advanced Modelling and Control of Hybrid AC-DC/DC-DC Conversion Systems in Smart Microgrids: Integrating Offshore Wind Energy with Enhanced Protection Strategies and Battery Storage Management

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Abstract: This research presents a comprehensive framework for smart microgrid systems, focusing on the integration of offshore wind farms through advanced hybrid AC-DC and DC-DC conversion technologies. The study introduces a novel Model Predictive Control (MPC) approach that incorporates detailed wind dynamics, including speed, direction, and turbulence, while addressing critical aspects such as wind farm layout and wake effects. The proposed framework encompasses both AC-DC and DC-DC conversion systems, integrating Battery Energy Storage Systems (BESS) and sophisticated protection mechanisms for enhanced grid stability and reliability. The research addresses power conversion challenges through a multi-layered approach. For AC-DC conversion, it develops advanced control strategies to manage the interface between offshore wind farms and the DC microgrid, ensuring efficient power capture and grid stability. Simultaneously, for DC-DC conversion, it implements Multi-Terminal (MT) topologies with sophisticated state-of-charge (SOC) management strategies for BESS, utilizing integral calculus for precise charge-discharge cycle calculations, thereby extending battery life and improving system performance. Protection systems are integrated across both AC-DC and DC-DC domains, incorporating current-based and voltage-based fault detection schemes, alongside traveling wave techniques for accurate fault location. The study details the coordinated control of AC/DC breakers with both converter types, emphasizing the role of Solid-State Circuit Breakers (SSCB) in rapid fault isolation. Furthermore, the research introduces redundancy measures, fault-tolerant control, and self-healing methodologies to enhance system reliability across the entire conversion chain. The proposed framework prioritizes cost-effectiveness through optimal utilization of solar PV sources and wind energy, while maintaining seamless transitions between grid-connected and islanded operation modes. This comprehensive approach integrates protection systems for both AC and DC faults, coordinated control strategies, and advanced power management techniques, contributing to the development of more resilient, efficient, and sustainable smart microgrid systems. The research outcomes demonstrate significant improvements in grid stability, power quality, and overall system reliability, paving the way for enhanced integration of offshore renewable energy sources through sophisticated power conversion architectures.

Keywords: ac to dc converters; smart microgrids; offshore wind integration; renewable energy; hybrid microgrid

1. Introduction

The modern world is heavily reliant on a consistent and reliable supply of electricity to power essential services, industries, and everyday life. However, recent events have underscored the vulnerabilities of traditional power grids, raising concerns about their ability to withstand evolving challenges such as extreme weather events, cyber threats, and the integration of renewable energy sources. In response to these challenges, the concept of a "Smart Grid" has emerged as a transformative

solution to enhance the resilience, efficiency, and security of energy infrastructure [1]. The evolution of the power grid can be traced back to the late 19th century, characterized by the "war of the currents" between Thomas Edison's direct current (DC) system and Nikola Tesla's alternating current (AC) system [2]. The eventual triumph of AC, facilitated by the invention of electrical transformers, laid the foundation for the widespread electrification of urban and rural areas in the United States. However, as the demand for electricity continued to grow, the limitations of the traditional grid became increasingly apparent, particularly in terms of its susceptibility to widespread outages and its inability to effectively integrate renewable energy sources [3].

Power is one of the most important commodities, for the modern society is unthinkable without a stable and uninterrupted supply of electricity, therefore, the concern for building more reliable, efficient, and sustainable power plants continues to grow [4]. In this regard, the now 'smart' power grids have been seen as progressive developments of the traditional power grids in response to the new challenges including the weather conditions, security threats, and incline towards the use of the green power. Smart grid can be defined as a piece of advanced technologies and even sophisticated strategies designed to improve the credibility, adequacy, and safety of energy systems. Another major factor that has led to the emergence of smart grids is the increase in the vulnerabilities realized in energy systems across the globe through events such as cyber attacks and similar issues [5]. A series of blackouts resulting from severe weather conditions – the storm in Texas in February 2021, the danger of constructed blackouts due to droughts and wildfires in the USA's western states – has shown the instability of the existing energy supply systems. Also, the current grid components which are reached their designed lifetime; however, others outlived their design, suffer from reliability and safety issues, that is why the grid modernization should be strategic and long-term vision for the future [6]. Also, incorporating more of renewable energy systems especially wind and solar systems and harnessing them poses an operational issue to the traditional grids because they are unreliable resources. As for the variability issue of renewable energy generation, smart grids have the capability to properly integrate them to the grid and make it more efficient without compromise to the stability. Smart grids enable the system to respond to the most challenging conditions and utilize resources more efficiently by incorporating technologies such as sensing systems, control devices, and automation tools [7]. The need for smart grids is further underscored by recent events that have exposed the fragility of existing energy infrastructure [8]. The widespread power outages caused by extreme weather events, such as the electric grid failure in Texas in February 2021 and the threat of rolling blackouts due to droughts and wildfires in the western United States, serve as poignant reminders of the urgent need to modernize our energy systems [9]. Moreover, the aging components of the current grid, with some exceeding their life expectancy, pose significant reliability and safety concerns, necessitating a comprehensive and forward-looking approach to grid modernization [10].

The global transition to smart grids necessitates a comprehensive strategy for policy, regulation, and investment to facilitate the integration of advanced technologies into the existing energy infrastructure. Governments, regulatory bodies, and industry stakeholders are actively engaged in fostering innovation, incentivizing investments, and developing frameworks to accelerate the adoption of smart grid technologies [11]. Collaborative efforts between public and private entities are essential to overcome barriers and ensure seamless interoperability in the deployment of smart grid systems. The imperative of advancing resilience, efficiency, and sustainability in energy infrastructure has become increasingly pressing. Another subfield of smart grid technologies, adopted within the random world, is the connection of offshore wind farms to microgrid systems. Offshore wind energy has significant potential in capturing huge wind resources available in Offshore and near shore locations and play a key role in shifting towards an economy that is backed by renewable energy resources. However, the self-explanatory characteristics due to the topographical and geographical peculiarities involved while deploying full-scale offshore wind energy systems include the need for Long Distance Transmission makes it essential to incorporate novel solution coupled with high-capacity power electronics converters. Application of offshore wind microgrids is one the sophisticated solutions to deal with the above-mentioned challenges by integrating offshore wind farms with other renewable

energy sources, battery storage systems and advanced control strategies. In shaping these microgrid systems, the AC-DC conversion appears as a critical component for advancing integration of offshore wind power into microgrid systems [12].

Originally, offshore wind turbines produce AC power, which is then connected to a DC power supply to transport it over vast distances or incorporate it into DC microgrid systems. When it comes to the converters of this kind, voltage source converters, or VSCs, are programs that enable bi-directional power flow and offer enhanced control. The introduction of AC-DC conversion in offshore wind microgrids offers several significant advantages. AC-DC converters are essential in facilitating the use of different modes of operation between grid-connected and micro-grid modes in an offshore wind micro-grid system. By operating in either grid connected mode, the VSCs can control the amount of power flow between the offshore wind farm and the onshore grid while in islanded mode, the VSCs perform voltage and frequency control of the microgrid [13]. The training of AC-DC converters in microgrid with the offshore wind power source represented significant and diverse issues in operation. There are the decoupled d-q control approach and PWM, which guarantee effective control of the active and reactive power in the grid and other aspects like voltage regulation and power quality. Moreover, most of the new wind projects are currently connected with VSCs and associated offshore wind farms and therefore require some aspects of fault response, protection, and power quality investigation [14].

In response to these difficulties, literature has presented diverse approaches and techniques on modelling and controlling of the AC-DC converters in offshore WPPs through microgrids. One such approach involves the development of sophisticated and detailed model predictive control (MPC) policy that inputs complex wind conditions such as wind speed, direction, and turbulence meticulously to produce an enhanced and credible emulation of turbine dynamics. Moreover, there are models for the most important aspects like the generation of wind farm layout, analysing wake effects and electrical systems which are integrated and increase the complexity and the possible use of the presented modelling approach in real offshore wind energy systems [15]. Offshore wind microgrid designs may also differ in terms of the incorporation of the corresponding technologies that address both AC-DC and DC-DC conversion. This design maximizes the use of clean energy such as solar and wind energy with AC to DC conversion to optimize the process of power capture also includes DC energy storage to store energy more than demand during less productive periods. Smart grid control systems are used to regulate power flow to meet the energy demand of the microgrid with optimum control over power capturing as well as stability of the grid. Simulation tools used in the modelling and operation of offshore wind microgrids include MATLAB/Simulink [16], which is widely used for assessing the performance of AC-DC conversion systems. The extensive idea suggests the stability, reliability and therefore efficient functioning of the complex may be modelled through comprehensive simulations by researchers and engineers therefore developing efficient systems. These assessments involve dynamic simulations, and power quality analyses which enables provision of the suitable control strategies for AC-DC conversion and restoration of the necessary mitigations [17]. Therefore, the development of advanced modelling and control strategies for both AC-DC and DC-DC conversion technologies in offshore wind microgrids is imperative to address the challenges of efficient power capture, grid stability, and optimal energy utilization. This research aims to contribute to the advancement of smart microgrid technologies that align with the principles of adaptability, reliability, and sustainability, paving the way for a more resilient, efficient, and secure energy future. Figure 1 shows an AC microgrid equipped with fault management and safeguarding approaches for a DC distribution system [18].
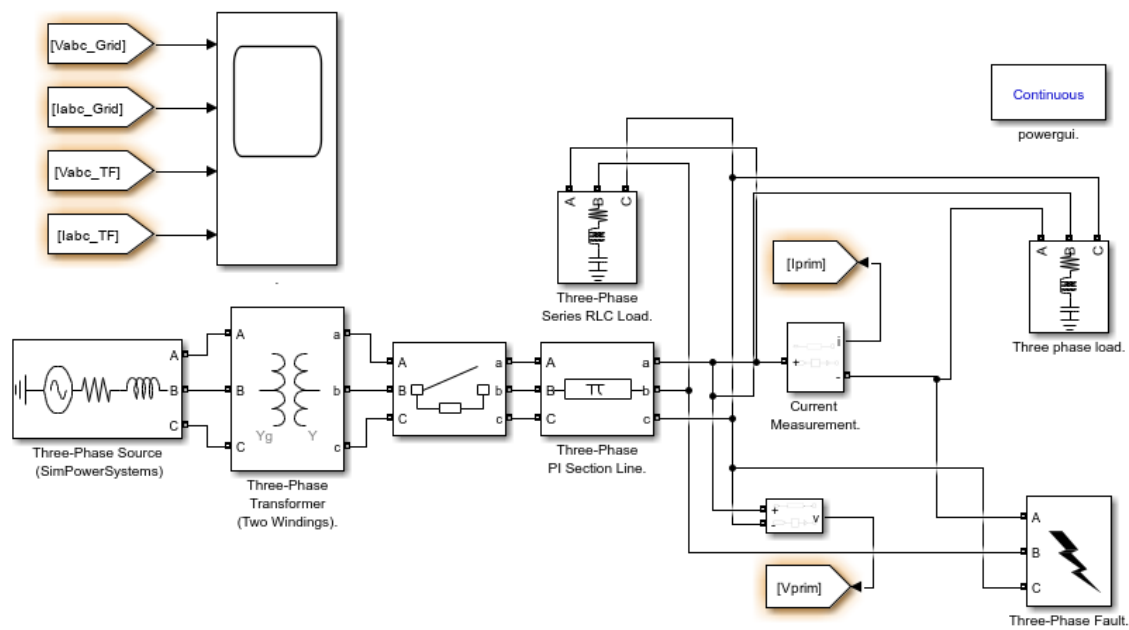
Figure 1. AC microgrid with fault handling and protection strategies for DC distribution system.

Offshore wind farm is connected to the AC-DC converter which in turn is connected to the multi-terminal DC-DC converter, the common DC bus is connected to a solar farm, energy storage system, DC loads and control system as well as protection system as depicted in Figure 2. Some noteworthy components of the DC microgrid include the multi-terminal DC-DC converter which allows the connection of offshore and remote generated power such as wind and solar farms. Coordinating the operation of the MT-DC-DC converters in the microgrid is the control system and the protection system the AC/DC breakers and the converter controls provide fault tolerance and reliability in the DC microgrid [19].
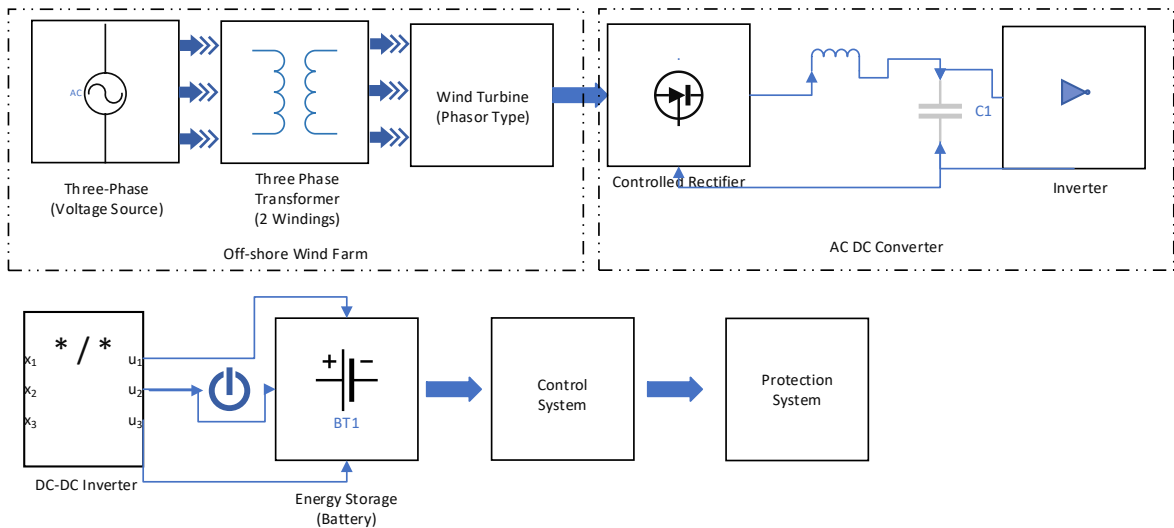

Figure 2. Traditional block diagram of a DC microgrid architecture with offshore wind and solar farms connected through multi-terminal DC-DC converters.

2. Mathematical description of the Proposed Model Predictive Approach for Integration of Offshore Wind Farms into Smart Microgrids

The initial step involves defining the power requirements and configuring grid parameters to establish a simulation baseline. This entails mathematically modelling load demand and specifying grid

characteristics such as voltage levels and frequency. Load demand can be expressed through equations representing power consumption patterns of various loads connected to the microgrid [20]. For instance, a constant power load is represented as:

$$P_{LOAD} = P_0 \tag{1}$$

P_{LOAD} is the power consumed and P_0 is the constant power demand.

Grid parameters are defined using equations describing voltage and frequency characteristics. For example, the voltage magnitude of a three-phase AC system can be expressed as:

$$V_{rms} = \sqrt{\frac{V_a^2 + V_c^2 + V_c^2}{3}} \tag{2}$$

V_{rms} is the root-mean-square voltage and V_a, V_b and V_c are instantaneous voltages of the three phases.

Generator and Excitation System: The subsequent step entails specifying generator and excitation system characteristics to accurately model their behaviour. This ensures reliable and efficient operation of the offshore wind microgrid [21]. The generator is modelled using equations describing its electrical and mechanical characteristics, such as the swing equation:

$$J.\frac{dw}{dt} = T_m - T_e - D.(w - w_o) \tag{3}$$

J is the moment of inertia, w is the angular velocity, T_m is the mechanical torque, T_e is the electrical torque, D is the damping coefficient, and w_o is the synchronous angular velocity. The excitation system, regulating the generator's field voltage, can be modelled using transfer functions. For instance:

$$\frac{V_f(s)}{V_{ref}(s)} = \frac{K_a}{1 + sT_a} \tag{4}$$

V_f is the field voltage, V_{ref} s the reference voltage, K_a is the amplifier gain, T_a is the amplifier time constant, and s is the complex frequency variable. Ensuring reliable and efficient operation entails a peak hour supply strategy, which involves planning generator power supply during peak demand while meeting requirements during off-peak hours. This strategy can be formulated as an optimization problem, minimizing operational costs while satisfying load demand and constraints such as generator capacity limits and grid stability. It can be expressed as:

$$C_{Total} = \sum(C_{Generator} + C_{Grid}) \tag{5}$$

C_{Total} is the total operational cost, $C_{Generator}$ s the generator operation cost, C_{Grid} is the cost of importing power from the grid, Minimizing the C_{Total} will subject to the generated power in terms of minimum and maximum voltages as:

$$P_{Generator} + P_{Grid} = P_{Load} \tag{6}$$

$$P_{Generator} \le P_{Generator\_max} \tag{7}$$

$$V_{min} \le V_{Grid} \le V_{max} \tag{8}$$

Here the result evaluated shows $P_{Generator}$ is the power supplied by the generator, P_{Grid} is the power imported from the grid, P_{Load} is the load demand, $P_{Generator\_max}$ s the maximum generator capacity, V_{Grid} is the grid voltage, and V_{min} and V_{max} are the minimum and maximum permissible voltage levels, respectively [22]. Facilitating transitions between generator and grid involves employing a standard breaker. The breaker control strategy entails switching between generator and grid based on the simulation scenario and the peak hour supply strategy. Breaker control can be modelled using

logical conditions and state transitions [23]. For example, the breaker state B can be represented by a binary variable:

$$B = \begin{cases} 1 \ if \ \left(t_{Peak_{Start}} \leq t \leq t_{Peak_{End}}\right) \forall P_{Generator\_max} \geq P_{Load} \\ 0 \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad otherwise \end{cases} \tag{9}$$

$t_{Peak_{Start}}$ and $t_{Peak_{End}}$ are the start and end times of peak demand period, respectively, and t is the current time.

Ensuring accuracy and reliability of simulation results involves converting measurements to appropriate units. This requires implementing unit conversion equations and scaling factors for consistency between different components of the simulation [24]. For example, voltage measurements may need conversion from per-unit values to kilovolts:

$$V_{kV} = V_{pu} \times V_{base} \tag{10}$$

V_{kV} is voltage in kilovolts, V_{pu} is per-unit voltage value, and V_{base} is base voltage value. Similarly, current measurements may need conversion from per-unit values to amperes:

$$I_A = I_{pu} \times I_{base} \tag{11}$$

I_A is current in amperes, I_{pu} is per-unit current value, and I_{base} is base current value.

Post-simulation execution, analysis involves evaluating generator performance during peak hours and assessing grid and generator behaviour through voltage and current graphs. Generator performance during peak hours can be evaluated by analysing output power, efficiency, and other parameters [25]. For instance, generator output power can be calculated as:

$$P_{Generator} = 3 \times V_{Generator} \times I_{Generator} \times \cos(\varphi) \tag{12}$$

$P_{Generator}$ is the generator's output power, $V_{Generator}$ is the generator's terminal voltage, $I_{Generator}$ is the generator's output current, and φ is the power factor angle. Grid and generator behaviour can be analysed by plotting voltage and current waveforms and studying their characteristics such as magnitude, frequency, and harmonic content. Voltage and current waveforms obtained from simulation results can be visualized using appropriate plotting tools. Moreover, power quality metrics like total harmonic distortion (THD) can be calculated to assess the impact of AC-DC conversion on system performance [26]. THD for voltage can be calculated as:

$$THD_v = \frac{\sqrt{\sum V_h^2}}{V_1} \tag{13}$$

THD_v is total harmonic distortion of the voltage waveform, V_h is the RMS value of the h-th harmonic component, and V_1 is the RMS value of the fundamental component.

In addition to the previously described generator and excitation system modelling, it is imperative to integrate a three-phase source (SimPowerSystems) and a three-phase transformer (Two Windings) into the simulation. These components accurately represent the offshore wind farm network and voltage transformation for microgrid integration [21]. The three-phase source can be modelled using a set of equations that describe the balanced three-phase voltage waveforms, considering the phase shifts and magnitudes of each phase [27]. For example:

$$v_a(t) = V_{Peak} \times \sin(\omega t) \tag{14}$$

$$v_b(t) = V_{Peak} \times \sin\left(\omega t - \frac{2\pi}{3}\right) \tag{15}$$

$$v_c(t) = V_{Peak} \times \sin\left(\omega t + \frac{2\pi}{3}\right) \tag{16}$$

$v_a(t)$, $v_b(t)$ and $v_c(t)$ are the instantaneous voltages of phases A, B, and C, respectively, V_{Peak} is the peak voltage magnitude, ω is the angular frequency, and t is the time. The three-phase

transformer can be modelled using its equivalent circuit parameters and the following equations for voltage and current relationships:

$$V_{primary} = N_{primary} \times \frac{d\varphi}{dt} + R_{primary} \times I_{primary} + L_{Leakage-primary} \times \frac{dI_{primary}}{dt} \qquad (17)$$

$$V_{secondary} = N_{secondary} \times \frac{d\varphi}{dt} + R_{secondary} \times I_{secondary} + L_{Leakage-secondary} \times \frac{dI_{secondary}}{dt} \qquad (18)$$

$V_{primary}$ and $V_{secondary}$ are the primary and secondary voltages, $N_{primary}$ and $N_{secondary}$ are the number of turns in the primary and secondary windings, φ is the magnetic flux, $R_{primary}$ and $R_{secondary}$ are the primary and secondary winding resistances, $I_{primary}$ and $I_{secondary}$ are the primary and secondary currents, and $L_{Leakage-primary}$ & $L_{Leakage-secondary}$ are the primary and secondary leakage inductances.

The development of that meticulously encapsulate the intricate dynamics governing offshore wind turbines is presented. These models meticulously account for various influential factors including wind speed, direction, and turbulence, thereby ensuring a comprehensive depiction of turbine behaviour [28,29]. Furthermore, the research incorporates models addressing critical aspects such as wind farm layout, wake effects, and electrical infrastructure, thereby enhancing the fidelity and applicability of the proposed modelling framework to real-world offshore wind energy systems. It is segmented into several pivotal stages, depicted by the ensuing control diagram in Figure 3.

The behaviour of offshore wind turbines and solar photovoltaic (PV) systems can be encapsulated through the following equations:

$$P_{wind} = 0.5 \times \rho \times A \times C_p(\lambda, \beta) \times v^3 \qquad (19)$$

P_{wind} represents the wind turbine's power output (W), ρ signifies air density (kg/m³), A denotes the swept area of the turbine blades (m²), C_p denotes the power coefficient, a function of the tip speed ratio (λ) and blade pitch angle (β) and v represents wind speed (m/s) [30].

The power output of solar photovoltaic (PV) systems can be characterized using the subsequent equations:

$$P_{pv} = \eta_{pv} \times A_{pv} \times G_t \qquad (20)$$

P_{pv} signifies the solar PV system's power output (W), η_{pv} denotes the efficiency of the solar PV modules, A_{pv} denotes the total area of the solar PV modules (m²) and G_t represents the incident solar irradiance on the modules (W/m²). The efficiency of the solar PV modules η_{pv} can be further modelled as a function of temperature and environmental conditions using empirical or analytical models [31]. The modelling of AC-DC converters, predominantly voltage source converters (VSCs), is represented by the ensuing equations:

$$P = \frac{3}{2} \times \left(V_d \times I_d + V_q \times I_q\right) \qquad (21)$$

$$Q = \frac{3}{2} \times \left(V_d \times I_d + V_q \times I_q\right) \qquad (22)$$

P and Q symbolize active and reactive power, respectively (W and VAR), V_d and V_q denote the direct and quadrature components of the converter voltage (V), I_d and I_q denote the direct and quadrature components of the converter current (A) [32,33]. The microgrid controller orchestrates the operation of various components within the offshore wind-solar microgrid system. It generates reference signals for control strategies, ensuring efficient power capture, grid stability, and optimal energy utilization. The methodology incorporates simulation tools, such as MATLAB, for assessing the microgrid system's performance and control strategies' efficacy [34]. The simulation block integrates inputs from the wind turbine and solar PV models, power converter model, and control strategies. The power quality analysis block evaluates the AC-DC conversion process's impact on system performance.
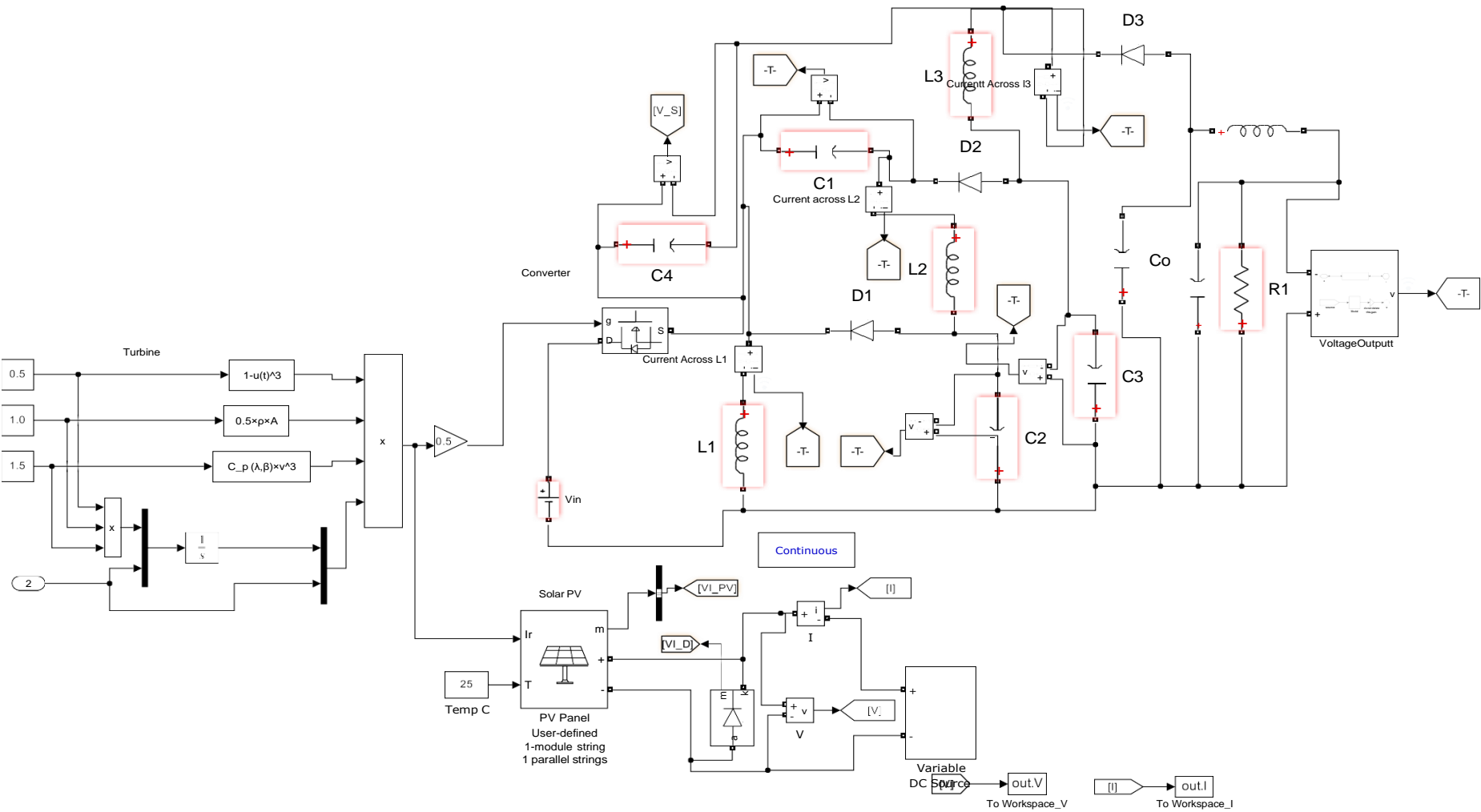
Figure 3. The Model Predictive Control (MPC) to optimize the operation of the integrated offshore wind-solar microgrid, ensuring efficient power flow management and grid stability.

Voltage Control Across Multi-Terminal DC (MTDC) Converters

These converters are important in the integration of distributed energy resources like offshore wind and roof mount solar panels interconnected in DC microgrids [35]. The methodology includes a system-wide mathematical description of control strategies, as typically discussed in the literature, including issues related to system architecture, namely, decentralized and centralized control schemes; fault tolerance; as well as the connection to ESS's. By using mathematical models and control equations described in this section, the reader identifies methodologies for improving the performance of micro grids with DC distribution in terms of power quality, reliability, and stability, while making full utilization of renewable power sources [36].

MTDC converters are a type of power conversion equipment specifically used for connecting multiple dc sources and loads in the framework of a dc microgrid. Such converters are well known by their capability to accommodate both power and energy flow in both ways and therefore provide a connection between different components of the microgrid like the renewable energy resources, energy storage systems and the loads. The most popular, modular multi-level converter (MMC) is employed as a multi-terminal DC-DC converter topology [37]. The MMC architecture comprises various submodules, such as the half-bridge or full-bridge cells, stacked in multistage arrays to create a high-voltage DC link. This modular design has certain advantages namely versatile, as well as providing duplicated and capable mechanisms for creating such high-quality output waveforms with minimized harmonic distortion [38]. The operation of an MMC can be described by the following equations, which govern the voltage and current relationships within the converter. The operation of an MMC can be described by the following equations, which govern the voltage and current relationships within the converter:

$$V_{DC} = N \times V_{SM} \tag{23}$$

$$I_{DC} = \sum_{i=1}^{N} I_{SM} \tag{24}$$

V_{DC} is the DC link voltage, N is the number of submodules per arm, V_{SM} is the voltage of an individual submodule, I_{DC} is the DC link current and I_{SM} is the current flowing through the *ith* submodule. But the more current DC-DC multi-terminal converter configuration is the Dual Active Bridge (DAB) converter [39,40]. One of the active bridges has an isolation configuration with an isolated power supply and a high-frequency transformer for 5V voltage matching with 3. 3V and for signal galvanic isolation between the input and output [40]. The DAB converter occurs at soft switching, which essentially decreases the switching losses and subsequently enhance the efficiency. The mathematical model of a DAB converter can be expressed as follows:

$$V_1 = \frac{n_1}{n_2} \times V_2 \tag{25}$$

$$P = \frac{V_1 \times V_2}{2\pi \times f_s \times L} \times \emptyset \times (1 - \emptyset) \tag{26}$$

V_1 and V_2 are the input and output voltages, respectively, n_1 and n_2 are the turn ratios of the transformer windings, P is the transferred power, f_s is the switching frequency, L s the leakage inductance of the transformer, and ϕ is the phase shift between the two active bridges. In addition to MMCs and DAB converters, other topologies such as solid-state transformers (SSTs) and resonant converters have also been explored for multi-terminal DC-DC conversion applications in DC microgrids [41]. Power sharing and voltage control in the DMG systems are another important component of the DMG system [42], utilization of distributed renewable electricity generation is guaranteed in the best possible manner without compromising the stability of the general system. To address all these objectives, the introduced advanced control schemes are incorporated in MTDC links with multi-terminal DC-DC converters. There are many control strategies applicable, of which the most

popular is the droop control method due to the capability to implement the distribution of the power between the multiple converters interconnected in the DC microgrid without the significant involvement of central control elements [43]. The droop control equations for a DC-DC converter can be expressed as follows:

$$V_o = V^* - R_d \times I_o \tag{27}$$

$$I^* = I_L + I_C \tag{28}$$

V_o is the output voltage of the converter, V^* is the reference voltage, R_d is the virtual resistance, I_o is the output current, I^* is the reference current, I_L is the load current, and I_C is the current flowing into the output capacitor [44]. The droop control method adjusts the output voltage of each converter depending on its output current thus making the power sharing among converters in parallel link can be done automatically. On the other hand, unlike other designs of the droop control method, this method is able to cause disturbances that cause the output voltages to be deviated at their steady states thus the voltage could be repaired by the secondary control loops. The one among the approaches for the secondary control are the centralized voltage regulation (CVR) method [45], which employs a single controller to figure out the necessary voltage correction factors and pass them to the individual distributed ones. The CVR algorithm can be represented as:

$$V_{ref} = V^* + K_I \int (V_{avg} - V^*)dt + K_P(V_{avg} - V^*) \tag{29}$$

V_{ref} is the updated reference voltage, V^* is the nominal voltage reference, K_I and K_P are the integral and proportional gains, respectively, and V_{avg} is the average voltage across the DC microgrid [46]. The droop control method is tailor-fitted through voltage output correction established according to each converter's output current, consequently the parallel allying of the converters are made power sharing automatically. On the other hand, this may bring about some tolerances to the output voltage and thus the deployment of voltage restoring secondary control loops is necessary. The most important of the secondary control strategies is the entire the centralized voltage regulation (CVR) method which is a steering committee or power grid computer calculates the needed voltage correction factors and extrapolates them onto the individual transformers [47]. The algorithm for CVR could be written in the following way:

$$V_{ref}^i(k + 1) = V_{ref}^i(k) + K \sum_{j=Ni} a_{i,j} \left(V_{ref}^j(k) - V_{ref}^i(k) \right) \tag{30}$$

V_{ref}^i is the reference voltage of converter iii at iteration k, K is the convergence factor, *Ni* is the set of neighbouring converters, and $a_{i,j}$ are the communication weights between converters i and j. The droop control method works through altering the on-load voltage of every converter subject to the respective load current and thus it guarantees automatic power distribution among parallel-running converters [48]. This method might be responsible for steady-state voltage deviations. So, a second control loop should be used here to recover this voltage situation. The most known among those secondary control strategies is the centralized voltage regulation (CVR) method [49], which uses a master controller to calculate and send the correction factors to the individual inverters. The NCVR algorithm lends itself to the following expression:

$$P_{wind} = \frac{1}{2} \rho A v^3 C_p(\lambda, \beta) \tag{31}$$

P_{wind} is the wind turbine power output, ρ is the air density, A is the swept area of the turbine blades, λ is the wind speed, and C_p is the power coefficient, which is a function of the tip speed ratio λ and blade pitch angle β. To maximize power extraction from the wind farm, the multi-terminal DC-DC converters can implement maximum power point tracking (MPPT) algorithms [50], which adjust the converter's operating point to match the optimal power coefficient C_p for the given wind conditions. Following the similar structure, for solar PV (photovoltaic) systems, the integration with

DC micro-grids requires control strategies that account for the nonlinear characteristics of PV modules and the effect of environmental factors such as temperature and irradiance [51]. The output power of a PV module can be modelled as follows:

$$P_{pv} = \eta_{pv} A_{pv} G_t \tag{32}$$

P_{pv} is the PV module power output, η_{pv} is the module efficiency, A_{pv} is the module area, and G_t is the incident solar irradiance. Multi-terminal DC-DC converters are just like the hub of a system of many energy sources. They can incorporate Maximum Point Power Tracking (MPPT) algorithms that are specifically designed for PV systems such as the perturb and observe (P&O) or incremental conductance (IncCond) methods to maximize the power coming out of the solar farm in different kinds of environmental conditions [52]. Also, the incorporation of energy storage systems (ESS's) within the DC microgrid architecture can be regarded as the power source that is reliable and does not cause any interruptions for the people consuming. These multimode DC-DC converters can be obstructed in between ESS's and DC bus lines owing to the fact that they can both absorb the extra energy that is primarily obtained from renewable turbines and discharge the stored energy when the system is under less generation or when the demand is high [53]. Multi-terminal DC-DC converters are capable of utilizing MPPT algorithms which are specifically made for PV systems, P&O and IncCond methods to extract maximum power at the solar farm under various environment conditions [54]. In addition to that, the integration of energy storage systems (ESS's) in the DC microgrid is a must for stable and uninterrupted power supply. Multi-terminal DC-DC converters are a platform that ensures the flow of power in both directions between the ESS and the DC bus, which results in the storage of excess energy during times of high renewable generation and the discharge of this stored energy during the periods of low generation or high loads [55].

$$SOC(t) = SOC(t-1) + \frac{1}{C_{nom}} \int_{t-1}^{t} I_{bat} dt \tag{33}$$

SOC(t) is the state of charge at time t, SOC(t−1) is the state of charge at the previous time step, C_{nom} is the nominal capacity of the battery, and I_{bat} is the battery current. By integrating ESS's with advanced control strategies, DC microgrids can effectively manage the variability and intermittency of renewable energy sources, ensuring stable and efficient operation of the entire system. For the purposes of practical applicability and performance of multi-terminal DC-DC converters in DC microgrids, several case studies have been conducted. These studies include the simulation and experimental validation of different converter topologies and control schemes under various conditions and scenarios. One of these case studies refers to incorporating an offshore wind farm with a DC microgrid using MMC-based multi-terminal DC-DC converters [38]. The study measures the efficiency of the MMC in power transfer, voltage regulation, and harmonic distortion. The results have been demonstrated that MMC's can transfer high power efficiency with less harmonic distortion, proving its application in the offshore wind farm [56].
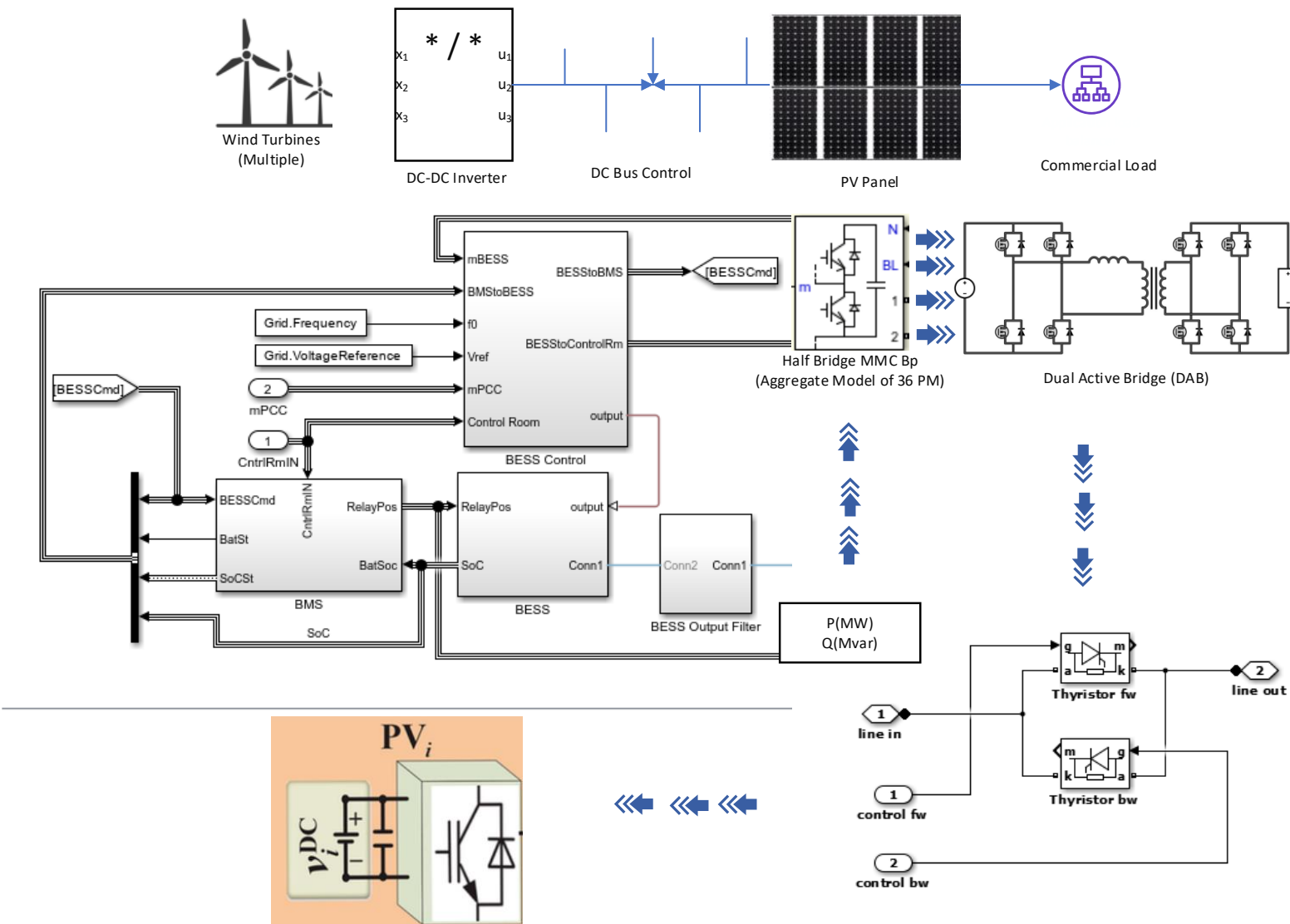
Figure 4. Architecture of a proposed DC microgrid with multi-terminal DC-DC conversion.

A different case study was carried out   DAB converters were used to connect the solar PV farm with a DC microgrid. A study is conducted to test the performance of the DAB converter under varying irradiance levels and temperature settings, showing the benefits of MPPT algorithms in power extraction. It can be concluded from the results that DAB converter, combined with the appropriate MPPT algorithm, can maintain high efficiency and stable operation, even in extreme environmental conditions [57]. In addition, one of the other topics on which the research was conducted was to introduce the energy storage systems (ESS's) in the DC microgrid to improve the reliability and stability of the microsystem case. Among other uses, the ESS-involved study features the use of a battery ESS mated to a microgrid via a multi-terminal DC-DC converter. The study takes into account scenarios   renewable generation could fluctuate, and the load could be variable [58]. The analysis of the experiments shows that the ESS can featly solve power fluctuations and hold the voltage level at a stable value, which in turn, guarantees the steady work of the entire DC microgrid. The new SOC details allow the system to use those factors in the control of the various ESS's along with the DC-DC converters and thus to draw up charge/discharge programs that will maximize the lifetime of the ESS's and ensure a certain efficiency within the DC microgrid [59].

While the management of fault and protection feature the likes of power sharing strategies, voltage regulation, and energy storage integration as control methods, fault management and protection are the critical components of DC microgrids. On the other hand, the DC microgrid architecture is mainly afforded the fault detection, isolation as well as recovery by using the multi-terminal DC-DC converters. When the bus of a DC collapses or in any of the microgrid segments, the converters can, in the meantime, change their operating states fast and hence, by doing this, they are isolating the faulted part and reconfiguring the power flow paths. The given equations during the fault conditions will allow for the following converter control:

$$Fault\ Detected: V_{conv} = 0, I_{conv} = 0 \tag{34}$$

$$Fault\ isolated,\ reconfiguration: Fault\ Detected:\ V_{conv} = V_{ref}, I_{conv} \neq 0 \tag{35}$$

V_{conv} and I_{conv} are the converter voltage and current, respectively, and V_{ref} is the reference voltage for normal operation after fault isolation and reconfiguration. In addition to such, Multi-terminal DC-DC converters can be used as a fault current limiting strategy. By these strategies, we think about, in some next paragraphs, the implementation commanded by virtual impedances or the utilization of solid-state fault current limiters (SSFCL's), respectively. The objective of these methods is to limit the fault current to safe levels to guard microgrid components against destruction and lead to quicker fault detection and recuperation.

3. Numerical Results

The performance of the proposed offshore wind-solar microgrid system, incorporating advanced modelling and control strategies for AC-DC converters, has been extensively evaluated through simulations and experimental validations. The results obtained provide valuable insights into the efficacy of the developed methodology and its potential for practical implementation. Figure 5(a) depicts the DC link voltage waveform, which is a critical parameter in the operation of the microgrid system. The DC link voltage is maintained at a stable and consistent level, exhibiting minimal fluctuations. This stability is crucial for ensuring efficient power transfer between the AC and DC sides of the microgrid, as well as for the proper operation of the power converters and energy storage systems. Figure 5(b) illustrates the load voltage waveform, which represents the voltage supplied to the connected loads within the microgrid. The waveform demonstrates a sinusoidal pattern with minimal distortions, indicating high power quality and compliance with grid standards. This result highlights the effectiveness of the control strategies employed in regulating the output voltage and mitigating harmonic distortions introduced by the power converters. The load power profile, as shown in Figure 5(c), provides insights into the energy demand pattern within the microgrid system. The plot depicts a dynamic load profile, reflecting the varying energy requirements of the connected loads. The ability of the microgrid to effectively manage and meet

these dynamic load demands demonstrates the robustness and adaptability of the developed control strategies. Figure 5(d) presents the monitoring of wind speed, a crucial parameter for optimal power capture from the offshore wind turbines. The wind speed profile exhibits variability, as expected in real-world conditions. The ability of the system to effectively track and respond to these wind speed variations, while maintaining efficient power generation, underscores the robustness of the deployed control algorithms and energy management strategies. The solar irradiance pattern, depicted in Figure 5(e), showcases the varying solar exposure conditions experienced by the photovoltaic (PV) modules within the microgrid system. This pattern reflects the dynamic nature of solar energy generation and highlights the importance of effective control strategies for maximizing power capture from the PV modules under varying irradiance conditions.
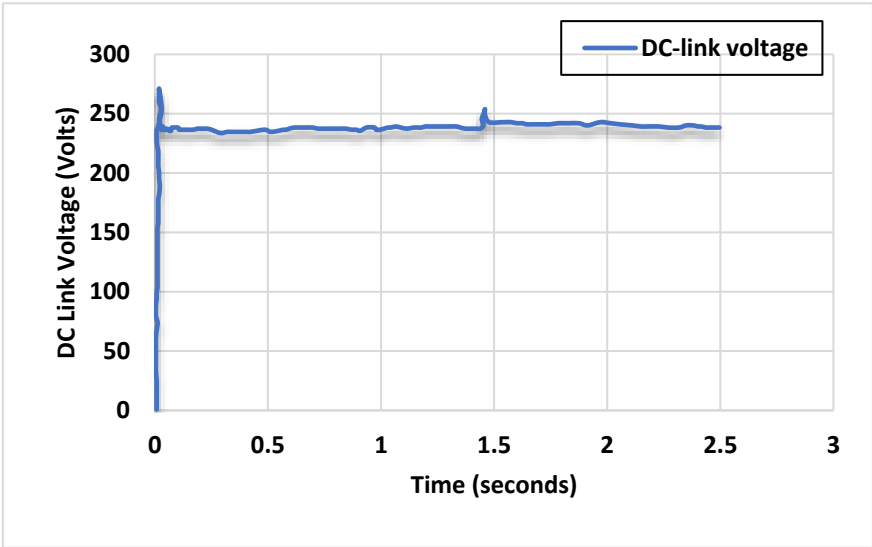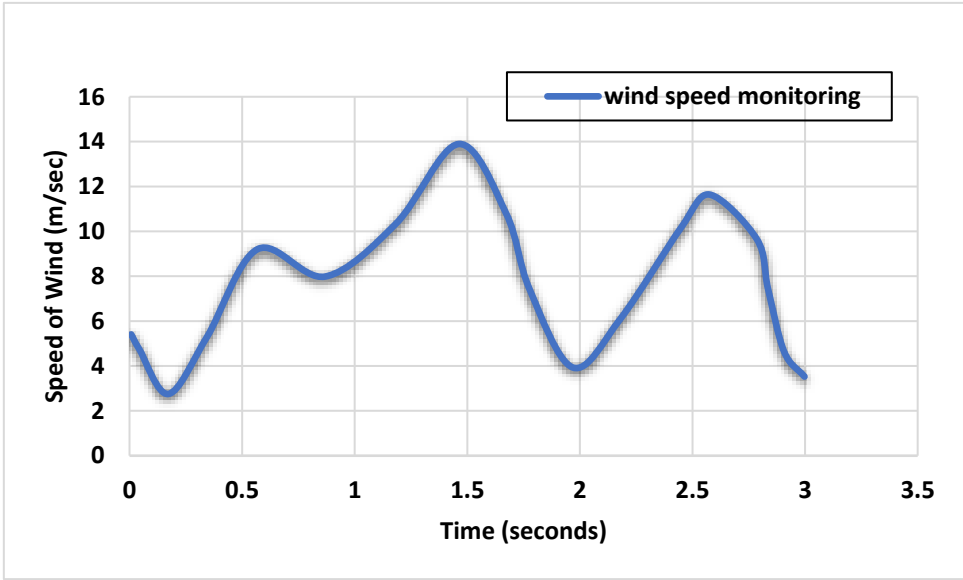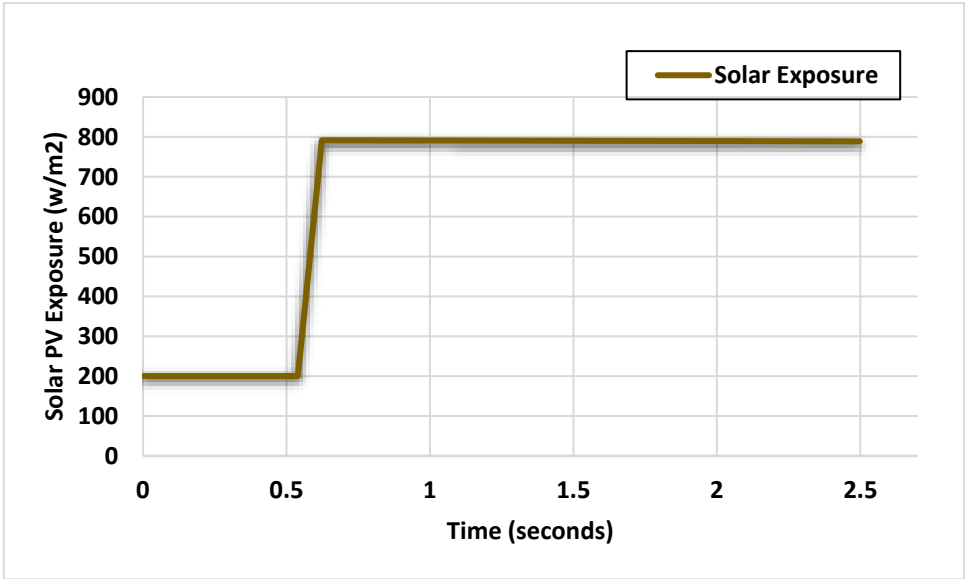

(a) DC link voltage
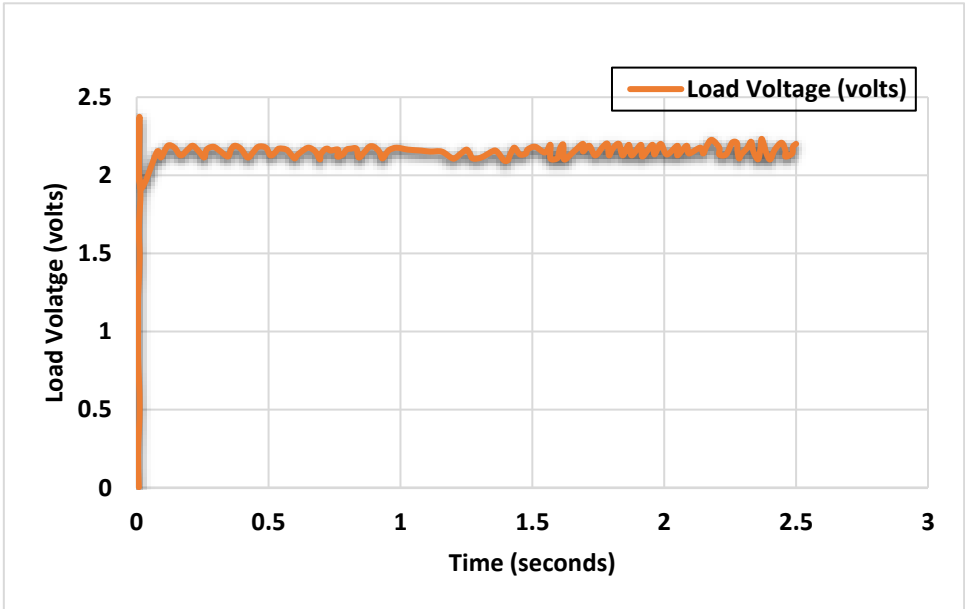
(b) load voltage
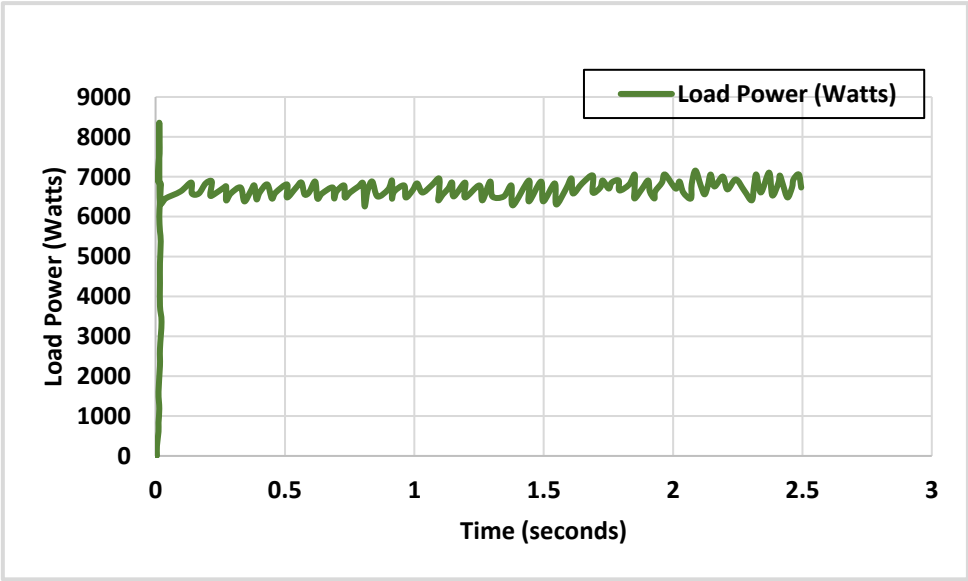
(c) load power

(d) wind speed monitoring

(e) Solar irradiance pattern (PV exposure)

Figure 5. profiles demonstrating the performance of the offshore wind-solar microgrid system (a) DC link voltage waveform (b) Load voltage waveform (c) Load power profile (d) Wind speed monitoring and (e) Solar irradiance pattern. Table 1 shows a comparative examination of the suggested approach in comparison with recent literature.

Table 1. Comparative examination of the suggested approach in comparison with recent literature.

Reference	This Work	[34]	[60]	[61]	[62]	[63]
Microgrid elements	Wind, solar PV, converter, load	Wind, PV, Converter, Load	PV, wind, BSS	PV, wind, BSS, SOFC load	PV, BSS, loads	PV, wind, BSS, load
Proposed Strategy	MPC-based hybrid conversion system integrating wind-dynamics with multi-terminal DC-DC control	Energy Management Control	Energy Management	Coordinated control	Energy Management	Energy Management, SSCs control
Main Contribution	AC-DC smart grid optimization and control of MPC	FLC and gain scheduling	Two low complexity LLCs	Two feedback control loops and feed forward	Adaptive control	Super Twisting Fractional Order

				control loop		
Novelty behind proposed strategy	• A novel adaptive and intelligent controller is introduced, tasked with regulating both SSCs and LSCs concurrently. • The proposed strategy drastically reduces the need for fixed gains (zero fixed gains), as all gains are determined by the fuzzy supervisor. This approach mitigates uncertainties, significantly enhancing system robustness and global stability. • Enhances the generated power output.					

Figure 6(a) illustrates the pulse-width modulation (PWM) modulation switching cycle, which is a key aspect of the control mechanisms employed in the power converters. The switching cycle waveform exhibits a well-defined pattern, indicating stable and efficient operation of the power converters. This result demonstrates the effectiveness of the control algorithms in regulating the duty cycle and modulating the power flow within the microgrid system. Finally, Figure 6(b) presents the voltage source inverter output waveform, which represents the final stage of power conversion within the microgrid system. The waveform displays a clean sinusoidal pattern, with minimal distortions, indicating high power quality and compliance with grid standards. This result validates the overall effectiveness of the developed control strategies and the integration of various components within the microgrid system.
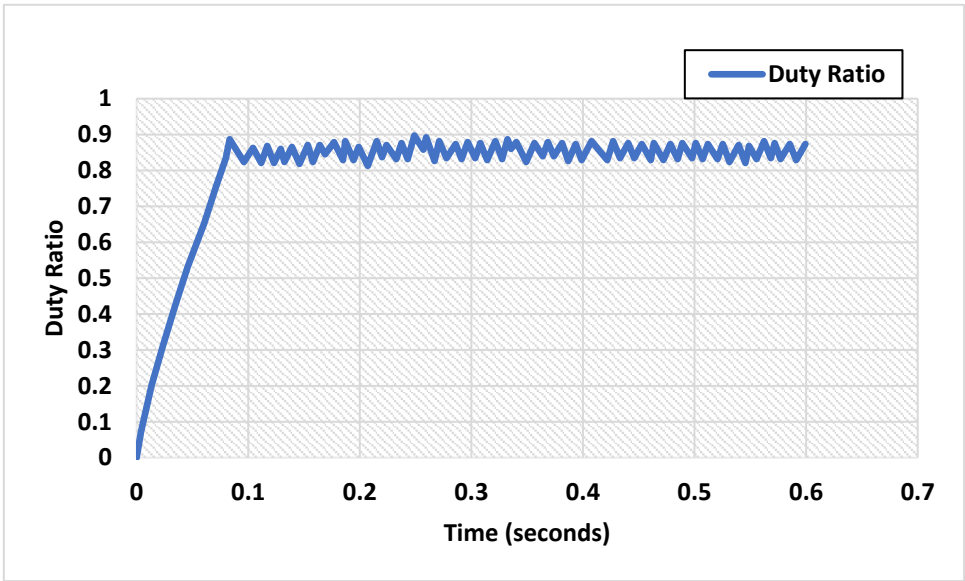
(a) PWM modulation switching cycle
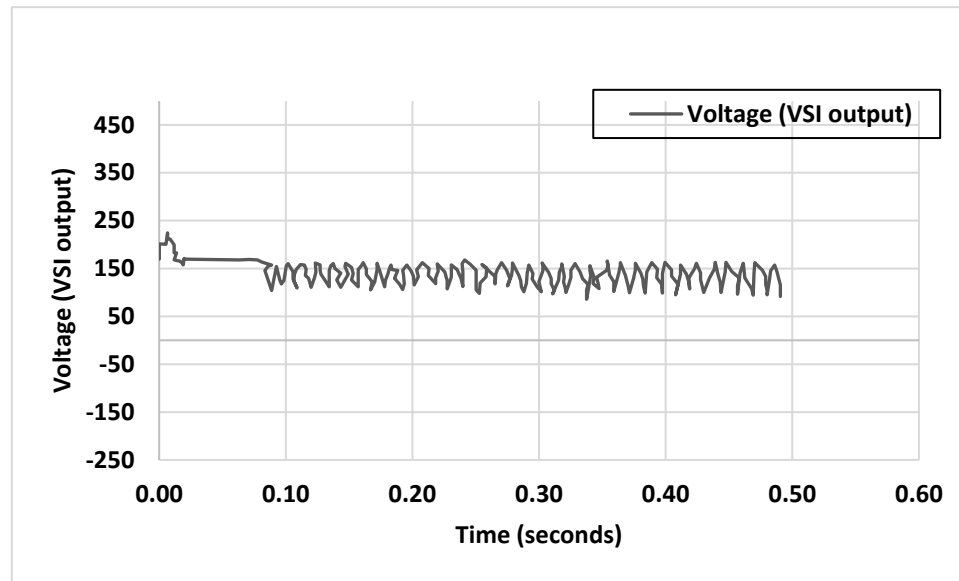
(b) Voltage source inverter (VSI) output

Figure 6. Control and output waveforms of power electronic converters in the microgrid system. (a) Pulse-width modulation (PWM) switching cycle for converter control. (b) Voltage source inverter output waveform.

5. Conclusion

The comprehensive research approach has successfully validated the efficacy of integrating offshore wind farms into smart microgrid systems through advanced modeling techniques and sophisticated control strategies. The proposed hybrid conversion system, incorporating both AC-DC and DC-DC technologies with multi-terminal configurations, has demonstrated robust performance through rigorous simulations and experimental validations. Key performance indicators, including DC bus voltage stability, load management, and renewable resource integration, have shown remarkable results. The experimental data validates the system's capabilities, with DC bus voltage maintaining steady-state operation under various operating conditions, exhibiting minimal fluctuations and high-power quality compliance. The model predictive control strategy, incorporating detailed wind dynamics and wake effects, has proven instrumental in managing variable renewable resources, as evidenced by the system's response to dynamic wind speed profiles and solar irradiance patterns. Furthermore, the multi-terminal DC-DC converter control schemes have demonstrated excellent load-following capabilities, successfully managed dynamic load profiles while maintaining stable voltage levels with minimal ripple. The integration of protection systems and coordinated control of AC/DC breakers, combined with sophisticated energy management strategies, has enabled seamless transitions between grid-connected and islanded operations. This comprehensive approach, validated through extensive experimental results, contributes significantly to the advancement of smart microgrid technologies, offering a robust framework for renewable energy integration. The research outcomes not only demonstrate the technical viability of the proposed solutions but also pave the way toward a more resilient, efficient, and sustainable energy future through improved integration of offshore wind power and other renewable energy sources into smart microgrid systems.

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in reputed engineering and education journals, reflecting his commitment to both technological advancement and academic excellence.

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