Optimisation of topology, rating, control and insulation coordination of a large series–parallel DC windfarm

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Abstract
This study presents the design of a large DC series-parallel windfarm that considers the key operational challenges in determining the optimal generator equipment rating and DC transmission voltage control. With this topology, offshore platform is not needed, but wind speed dispersion over windfarms and generator outage possibilities demand generator DC output voltages beyond their ratings. An optimization algorithm is developed along with a complete cost model, which includes operational and capital costs with all topology options, in order to inform design decisions. The results are evaluated on a 100-generator, 25×4, 1 GW, 525 kV test wind farm and performance is verified using detailed PSCAD/EMTDC time-domain simulation. The key finding is that a positive net present value (NPV) is achieved, avoiding power curtailment even under 3% generator outage, when an overvoltage coefficient of 1.145 pu is utilised on all wind generators, assuming use of a suitable DC transmission voltage control. Further, a wide-ranging parameter sensitivity analysis is performed, and tower arrangement for insulation requirements is proposed.

1 | INTRODUCTION

The DC collection system for offshore windfarms is an emerging topology with many potential benefits over the conventional AC collection system [1]. DC wind generators are also becoming more commercially accepted, and a pre-transformer configuration was proposed in [2] and [3], while DC wind generators with isolated DC/DC converter configurations were studied in [4] and [5]. The DC collection system topologies so far discussed in literature are the parallel, series–parallel (SP) and matrix interconnected (MI) topologies [6].

The parallel DC topology [7], which connects all generators to the medium voltage DC (MVDC) collection bus, and voltage is then stepped up using a central DC/DC converter, is characterized by high efficiency, flexibility and reliability. However, it requires an offshore platform to support large DC–DC converter.

The series DC topology attains transmission voltage level by adding generator DC voltages and brings the benefits of reduced footprint and cost savings due to the possible elimination of the large offshore platform [8, 9]. According to [10], a cost savings of up to 20 M€ for a small 160 MW windfarm is expected. One of the key challenges of the series topology is unequal power generation within a string (because of unequal wind speeds, generator faults or scheduled maintenance), requiring increased generator voltages (overrating). A current control could be used to reduce overvoltage [3, 8], but this reduces power output. Another challenge relates to insulation since the generator farthest from the ground point is required to withstand the full transmission voltage (>100 kV) while other units are insulated according to their distance from the ground point. The use of isolated DC/DC converters within the wind generator can reduce the number of components that will require high insulation level, but the cost implications are unknown.

The series-parallel (SP) DC topology utilizes several parallel-connected strings, each with a number of series-connected generators, to achieve a desired voltage and power level [5, 11]. It exploits the benefits of both parallel and series topologies, which means better reliability as well as efficiency at large wind farm powers. However, the issues of inadequate flexibility and unequal power generation persist. As the number of faulty (bypassed) units increases within a string, the overvoltage requirement increases considerably (cost implications), thereby leading to possible disconnection of the corresponding
string, which leads to revenue loss. The authors in [12] proposed a solution termed ‘the matrix-interconnected topology,’ which dynamically reconfigures the series-parallel topology by switching auxiliary paths between strings upon an overvoltage condition, leading to a DC system with better efficiency and availability. However, the cost of additional switch gears and overrated cables can significantly increase the initial investment cost of the windfarm. In [13], a solution using a generator voltage limitation control is proposed. This, however, translates to undesired power curtailment, as maximum power point tracking (MPPT) is disabled. [14] proposed a solution termed ‘the global overvoltage limitation strategy’ that continuously varies the transmission voltage (based on the prevailing wind condition) to achieve MPPT from the individual generators, but it depends on a somewhat higher rating on the generator’s equipment (DC/DC converter). The extent to which each generator equipment must be overrated and the corresponding financial impact are not considered. The study is focused on a small windfarm and lacks consideration of the generator outcome scenario and wind variation, which becomes a valid concern in a large windfarm. Considering the available body of knowledge, it is not clear if offshore DC collection systems are cost effective and what operational restrictions are required, especially with modern GW-size wind farms.

This paper presents a systematic design method for a large 1 GW series-parallel DC windfarm that simultaneously considers all the challenges of determining the optimal generator equipment rating, topology (number of strings) and transmission voltage control. We take into account all key aspects of operating conditions, like wind variation across windfarm (due to aerodynamic wakes) and generator outage possibilities. This study presents the impact of design choices on the capital expenditure, facilitating project business case evaluation. The expected implementation challenges (like insulation and control algorithms) are studied to illustrate feasibility and explore the impact on capital investments. The remainder of this paper is arranged as follows: Section 2 describes the system configuration and presents the design assumptions and constraints. Section 3 presents a design method for calculating generator equipment voltage ratings using MATLAB numerical model. Section 4 presents the key cost models. Section 5 proposes an insulation coordination of the generator equipment. Section 6 presents a parametric study of a 1 GW test case and a sensitivity analysis to validate the design methods. Section 7 presents a simulation of the 1GW test case developed in PSCAD/EMTDC. Finally, conclusions are drawn in Section 8.

2 | SYSTEM DESCRIPTION

2.1 | Windfarm power generation

Figure 1 depicts the studied DC series-parallel \( x \times y \) (\( x \) is the number of generators in a string, \( y \) is the number of strings in the windfarm) collection system. The DC wind generator consists of a permanent magnet synchronous generator (PMSG), an active rectifier facing generator and an isolated DC/DC converter. In this study, the current source converter (CSC)-based DC/DC topology, similar to the one proposed in [15], is employed. This topology also facilitates bidirectional power operation, which is essential for black-start and auxiliary load supply during island mode of operation (due to low wind speeds, outage, or scheduled maintenance).

An active voltage source converter (VSC), termed ‘Bridge 1’, is realized as a 3-phase 2-level VSC (3-Ph 2L-VSC) topology with space vector modulation (SVM) control. The isolated DC/DC converter employs ‘Bridge 2’, a medium frequency transformer (MFT) and ‘Bridge 3.’ Bridge 2 is a voltage source converter (2L-VSC) with 180° square wave modulation, considering higher fundamental frequency [15]. ‘Bridge 3’ is realized using a 3-phase thyristor-based topology with six-step modulation control referenced to the AC voltage waveform or gate signals of ‘Bridge 2’. It is worth mentioning that ‘Bridge 2’ can also utilize a neutral-point-clamped (NPC) topology as proposed in [15], which has the benefit of reduced commutation voltage for the thyristors and flexible voltage control capability that leads to lower switching losses (not used here because of complexity). The transmission voltage, \( V_{\text{HVDC}} \), is the sum of individual generator DC voltages in a string. A full bridge modular multilevel HVDC converter (FB-MMC) is employed onshore at the grid connection point to control the transmission voltage, which also benefits not only in scalability, modularity, reduced power loss, reduced AC voltage distortion, and good DC fault tolerance [15, 16], but also brings capability of operating either as a current source or as a voltage source [17].

The available power of a wind generator, \( P_{ij} \) (for \( i = 1, 2, \ldots, x \) and \( j = 1, 2, \ldots, y \)) depends on the local wind speed \( v_{w} \), which may vary across a windfarm, whereby generation starts at the cut-in wind speed, \( v_{c,i} \), and reaches rated power, \( P_{g,r} \), at the rated wind speed, \( v_{w,r} \), where it is maintained constant with the help of pitch control until the cut-out speed, \( v_{w,o} \), is reached. The power curve of a typical wind generator can be expressed as:

\[
P_{ij}(v_{w}) = \begin{cases} 
0, & \text{for } v_{w} < v_{c,i} \\
0.5 C_{p} \rho A v_{w}^{3}, & \text{for } v_{c,i} \leq v_{w} < v_{w,r} \\
P_{g,r}, & \text{for } v_{w,r} \leq v_{w} < v_{w,o} \\
0, & \text{for } v_{w} > v_{w,o}
\end{cases}
\]

where \( C_{p}, \rho \), and \( A \) represent the power coefficient, air density, and turbine blade swept area, respectively [18].

The total available windfarm power at each wind speed, \( P_{WT}(v_{w}) \), is then given as:

\[
P_{WT}(v_{w}) = \sum_{j=1}^{y} \sum_{i=1}^{x} P_{ij}(v_{w})
\]

Because of turbulence, predominant wake effects and depending on the adopted windfarm layout, unequal wind speeds are experienced by the different generators leading to unequal power generation [19]. Because of the common current...
in string \( i_{\text{string}} \), unequal power generation implies unequal voltage at the output DC terminals of the generators’ DC/DC converters, \( V_{\text{deg},i} \) (for \( i = 1, 2, \ldots, x \)).

The unconstrained DC voltage of the \( i \)th generator’s DC/DC converter in the \( j \)th string, \( V_{\text{dcg},ij} \) (for \( i = 1, 2, \ldots, x \) and \( j = 1, 2, \ldots, y \)) is given as:

\[
V_{\text{dcg},ij} = \frac{P_{g,ij}}{\sum_{x=1}^{x} P_{g,ij}} V_{\text{HVDC},r}
\]

where \( \sum_{x=1}^{x} P_{g,ij} \) is the total power of the \( j \)th string and \( V_{\text{HVDC},r} \) is the HVDC transmission line voltage.

The current in a \( j \)th string, \( i_{\text{string},j} \) (for \( j = 1, 2, \ldots, y \)) is given as:

\[
i_{\text{string},j} = \frac{\sum_{x=1}^{x} P_{g,ij}}{V_{\text{HVDC},j}} = \frac{P_{g,ij}}{V_{\text{deg},ij}}
\]

For a given windfarm power generation, \( P_{\text{WF}} \), string currents and HVDC current, the instantaneous power delivered onshore, \( P_{\text{onshore}} \), is given by:

\[
P_{\text{onshore}} = P_{\text{WF}} - P_{\text{UP}}
\]

where \( P_{\text{UP}} \) represents the undelivered power, which consists of curtailed power and system losses.

### 2.2 Assumptions

The following initial assumptions are employed in this paper:

1. The wind speed on generators in the windfarm will be a random number, with a given variation range \( D_{\text{deg,ws}} \) between the largest and lowest wind speeds. The mean value of wind speed will be varied between scenarios. The power difference experienced at the downstream wind generators in a large windfarm can reach up to 50% under wake conditions [20].
2. A number of generators under outage, \( F_{\text{max}} \), will be considered, with a maximum of one generator outage per string \( (F_s) \) for configurations with more than two strings.
3. All the wind generators are equipped with controllers that balance electrical power and available mechanical power by changing the DC voltage on the machine (DC current is common for a string).
4. Additional controllers activate the blade angle regulator to reduce power when converter stresses approach rated values (DC voltage and DC current).

### 2.3 Power curtailment

The DC power from \( i \)th generators’ DC/DC converter in the string \( j \), \( P_{\text{gear},ij} \), at curtailment is given by:

\[
P_{\text{gear},ij} = V_{\text{deg},ij} I_{\text{string},j}
\]

where \( V_{\text{deg},ij} \) is the rated DC voltage and \( I_{\text{string},j} \) is the instantaneous-string current (lower than rated). Subtracting generator power (6) from available power \( P_{g,ij} \) in (1), we obtain spilled (or curtailed) power for each generator, which is then summed to obtain the curtailment for the whole windfarm. This is given by:

\[
P_{\text{curt}} = \sum_{j=1}^{y} \sum_{x=1}^{x} (P_{g,ij} - P_{\text{gear},ij})
\]

### 2.4 System losses

The system losses in a windfarm, \( P_{\text{losses}} \), consist of the following components: converter (PEC) losses, \( P_{\text{PEC,loss}} \) cable losses (i.e.,
collection ($P_{c-loss}$) and transmission ($P_{f-loss}$) given by:

$$P_{losses} = P_{PEC-loss} + P_{c-loss} + P_{f-loss} \quad (8)$$

2.4.1 Power electronic converter (PEC) losses

The PEC losses in each VSC bridge (1 and 2) are the sum of conduction and switching losses in both IGBT and diode [6]. The total losses in bridge 3 (i.e., conduction and switching losses of the thyristor) are calculated following the loss model provided in [21].

2.4.2 Cable losses

The losses in the DC collection and transmission cables are calculated following the loss model in [11].

3 DESIGN ALGORITHM FOR GENERATOR EQUIPMENT VOLTAGE RATING

3.1 Overvoltage coefficient considering generator outages only

The transmission voltage is usually maintained at the nominal level by the onshore converter in order to minimise losses. The rated transmission voltage is not increased beyond the nominal value (i.e., $V_{HVDC,r} = V_{HVDC,nom}$, as transmission equipment is costly. The corresponding voltage $V_{deg,nom}$ and current $i_{string,nom}$ of a generator assuming rated wind speed on all generators are labelled nominal as expressed below:

$$V_{deg,nom} = \frac{V_{HVDC,nom}}{x} \quad (9)$$

$$i_{string,nom} = \frac{P_{string,nom}}{V_{HVDC,nom}} \quad (10)$$

where $V_{HVDC,nom}$ and $P_{string,nom}$ are the nominal string voltage (kV), number of generators in a string and the nominal string power (MW), respectively.

In an event where the generators in a string are unable to provide transmission voltage (i.e., when some units are out of service or because of different wind speeds), the string will be required to shutdown (also termed ‘string failure’) [10]. To avoid this, we are trying to optimise the converter voltage rating, $V_{deg,i,j}$ which is obtained using the overvoltage coefficient $\alpha_{ov}$.

$$V_{deg,i,j} = (V_{deg,nom} \times \alpha_{ov}) \quad (11)$$

This voltage rating applies only to bridge 3 in Figure 1. The bridges 1 and 2 retain the same nominal voltage and current rating. ‘Optimal value’ in this paper is defined as the lowest-cost value that can maximise power delivery from the windfarm under given conditions and assumptions.

The first overvoltage coefficient $\alpha_{ov,first}$ (in line with study in [10]) considering just the given maximum number of outage generators per string, $F_{ij}$, is obtained when all generator powers are at their rated levels:

$$\alpha_{ov,first} = \frac{V_{HVDC,nom}}{V_{deg,nom}(x-F_{ij})} \quad (12)$$

Adopting this coefficient can maximize power extraction from the wind farm only when the powers are equal at individual generators. This means that the first overvoltage coefficient is valid only at the mean wind speeds higher than rated, as individual blade-angle controls curtail wind power to rated value on each individual machines.

3.2 Consideration of HVDC voltage control

3.2.1 Online optimal DC voltage control

It is known from previous studies [10, 14], that lowering the HVDC voltage at lower wind speeds is an operational strategy that can reduce/eliminate the curtailment losses, which will result in maximized power extraction and improved profit despite increase in conduction losses.

This study takes account of the same DC transmission voltage control (in the manner done in [14]) in the design stage, in order to find the optimal equipment rating. It is expected that we will obtain lower required overrating when active DC voltage control is considered.

According to [14], an optimal HVDC voltage level $V_{HVDC,opt}$ lies in the range between the rated $V_{HVDC}$ and a minimum HVDC voltage $I_{HVDC,min}$. The $I_{HVDC,min}$ is the minimal DC voltage that avoids curtailment. It can be obtained considering the rated converter voltage $V_{deg,i,j}$, total power generation in string $j$, $P_{string,j}$, and the power of highest generating unit in string $j$, max($P_{i,j}$), as expressed below:

$$V_{HVDC,min} = \min \left( \frac{\sum_{i=1}^{x} P_{i,j}}{\max(P_{i,j})} \right) \quad (13)$$

The HVDC voltage is varied by onshore converter until the maximum power operating point is reached under the given conditions. In practice, an online closed loop control can be utilized, which will follow some maximum power point tracking (MPPT) approach, like those used for wind and PV power systems [22]. The controller utilizes the HVDC voltage ($V_{HVDC}$) and current ($I_{HVDC}$) signals measured on the grid side, as shown in a control schematic in Figure 2. These are used to obtain the power of the windfarm, which is digitized using a sampler. The difference between the sampled and output power, $\Delta P$, is considered a true derivative of the output power and is used to determine the direction of the power change. A PI controller is then utilized to drive $\Delta P$ to zero, which indicates
3.2.2 DC voltage control implemented in design algorithm

The calculation of optimal DC voltage is illustrated in Figure 3a, and represents the first step in the design algorithm. For a given mean wind speed ($v_{w,i}$), and variation range ($v_{w_{ci}} \leq v_{w} < v_{w_{co}}$), the algorithm determines the unconstrained power on generators, $P_{deg,i,j}$, and considers the overvoltage coefficient as a variable input. Powers of individual wind generators (which depend on mean wind speed) are generated randomly within the given range. It then computes $V_{HVDC, min}^{*}$ and searches the range between $V_{HVDC, min}^{*}$ and $V_{HVDC, opt}^{*}$, and returns the value of the voltage $V_{HVDC, opt}^{*}$ where the maximum power is attained.

3.3 Optimal equipment voltage rating

The worst-case overvoltage requirement may happen at any wind speed, and therefore, full range of wind speeds should be examined. Also, the assumed variation in wind speeds, $Dev_{max}$, will cause further power variation on individual generators. Because of the common DC current in a string, this means that some generators would have a high DC voltage stress that exceeds overvoltage rating calculated previously $\alpha_{ov, first}$ in Section 3.1.
The optimal overvoltage coefficient $\alpha_{\text{ov, opt}}$ can be derived considering that the transmission voltage follows the optimal DC voltage $V_{\text{HVDC, opt}}^*$, for all wind speeds. To obtain the required overvoltage coefficient, a numerical iterative design algorithm is developed in MATLAB as shown in Figure 3a,b, because of the complex nature of the analysis making the use of explicit formula unfeasible. The algorithm takes key input variables and numerical parameters such as windfarm size ($x \times y$), rated generator power ($P_{\text{gen}}$), wind speed on machines ($u_{\text{ij}}$), overvoltage coefficient and optimal HVDC voltage ($V_{\text{HVDC, opt}}^*$) from subroutine in Figure 3a. The algorithm computes $\alpha_{\text{ov, init}}$ (which is the difference between the new ($\alpha_{\text{ov, new}}$) and initial ($\alpha_{\text{ov, init}}$) overvoltage coefficients) and this is repeated until variables converge within small tolerance (ToI). The process repeats for each wind speed in the predefined range. The optimal coefficient is then taken as the highest recorded value for $\alpha_{\text{ov, new}}$ in the range of wind speeds.

### 4 | COST MODEL

Cost is the final indicator, which consists of the investment costs and costs incurred during the windfarm’s operational lifecycle. Cost parameters are adopted from the models reported in [6, 18, 23–25] and given in Table A1 in the Appendix.

#### 4.1 | DC wind generator cost

The considered DC wind generator is still in the research and development stage; therefore, the capital cost is estimated based on the cost of the existing Type 4 AC wind generator $C_{\text{WTAC}}$ (excluding the cost of the grid-facing bridge and 50 Hz transformer), while the cost of a DC/DC converter $C_{\text{DC/DC}}$ of the same rating is estimated as reported in [23, 24].

Foundations take up a significant portion of the overall generator cost, especially when installed far offshore. The cost of a monopile foundation $C_f$ as estimated in [25] is utilised.

The cost of a single DC wind generator $C_{\text{WTDC}}$ (M€) is expressed as:

$$C_{\text{WTDC}} = 1.1 \times \left( C_{\text{DC/DC}} + C_{\text{WTAC}} + C_f \right)$$  \hspace{1cm} (14)

$$C_{\text{WTDC}, T} = 1.1 \times N_{\text{WT}} \times C_{\text{WTDC}}$$  \hspace{1cm} (15)

where $N_{\text{WT}}$ is the total number of wind generators in a windfarm while the coefficient 1.1 represents the transportation and installation cost of the DC turbines.

#### 4.2 | MVDC collection and HVDC transmission system costs

The MVDC collection system consists of inter-array cables and MVDC switchgears, while the HVDC transmission system consists of the transmission cables and HVDC switch gears. The cost of DC switch gear (£) $C_{\text{DC, switch}}$ (MV or HV) is assumed to be four times the cost of AC switch gear because of the lack of information on the cost of installed DC switch gear as given in [6]. Other costs are estimated using the cost data reported in [18] and [23].

#### 4.3 | Initial investment cost

The initial investment cost $C_{\text{INVEST}}$ is the sum of the total windfarm cost, $C_{\text{WT, T}}$ and project development cost, which is estimated as a percentage of $C_{\text{WT, T}}$ [25].

#### 4.4 | Annual revenue and loss in revenue

The annual revenue, $A_{\text{Revenue}}$ (M€), which consists of income generated by the windfarm, and the annual loss in revenue, $A_{\text{LossRev}}$ (M€), are expressed as seen in “(19) and (20)” where $f(t_w)$ is the Weibull probability distribution function of occurrence of each wind speed [6]. The most common case for the Weibull distribution (i.e., $k = 2$ (Rayleigh distribution)) and $\lambda = 8.88$ m/s is employed in this study.

The annual profit $A_{\text{Profit}}$ (M€) of a windfarm is expressed as:

$$A_{\text{Profit}} = A_{\text{Revenue}} - C_{\text{O&M}}$$  \hspace{1cm} (16)

where $C_{\text{O&M}}$ is the annual windfarm operation and maintenance (O&M) cost as estimated in [24].

#### 4.5 | Net present value (NPV) and simple payback time (SPT)

The net present value (NPV) gives an idea of the worthiness of a project while the simple payback time (SPT) indicates the production period required for the initial investment to be repaid. These are given by:

$$\text{NPV} = \sum_{t=0}^{T} \frac{A_{\text{Profit}}}{(1 + r)^t} - C_{\text{INVEST}}$$  \hspace{1cm} (17)

$$\text{SPT} = \frac{C_{\text{INVEST}}}{A_{\text{Profit}}}$$  \hspace{1cm} (18)

where $r$ represents the annual profit discount rate.

### 5 | COST OF HIGH-VOLTAGE INSULATED GENERATORS

The wind generators will be stressed to different voltages depending on location, as depicted in a string. Because of possible outages, and for standardization reasons, we assume that all generators will be rated for the location with worst-case voltage stress. The main concern here relates to the insulation distances
within the wind generator tower. State-of-the-art 10–15 MW wind generators utilize around 8.0 m diameter tower base as a conservative representation [26]. Our calculations show that this space will not be sufficient to accommodate HV platform and equipment on the platform (MF transformer and bridge 3). An additional housing for HV equipment is assumed beside the tower as shown in Figure 4, and also discussed in [15].

According to IEC EN 60071-1 [27], the minimum required phase-to-earth air clearance for 362 kV RMS (or 525 kV DC) is given as 2.9 m for rod-plane structure. The dimensions of the equipment on the HV platform are determined considering line-line voltage (which is quite low, and there are many installations). The dimensions of the converter cabinet can be estimated from those of existing large MW generators [28]. However, since the development of MW rated MFTs is still in its early stages, obtaining accurate dimensions is difficult.

A 5 MW 1 kHz MFT was developed in [29], while a 10 MW 5 kHz MFT prototype is proposed in [30]. Both MFTs are approximately ten times lighter with smaller footprint compared to a 50 Hz transformer of equivalent ratings. By assuming a linear relationship between frequency and size, a 10 MW 200 Hz MFT will have a weight and size of around 0.15 pu compared to a 50 Hz transformer of equivalent rating (weight is 21 tons). This shows that there is no significant difference in dimension. Therefore, for illustration purposes, the dimension of a 10 MW 50 Hz 6.3/33 kV MFT will be utilized [30].

The cabinet on the platform will be smaller than conventional units since only bridge 3 is used. The proposed layout and insulation distances (drawn to scale) are illustrated in Figure 4. The dimensions of DTU’s 10 MW reference wind turbine mounted on a monopile substructure are used to draw the turbine’s structure to scale [31].

\[
A_{\text{Revenue}} = \frac{\left( r_{\text{onshore}} \int P_{\text{onshore}}(r_w) f(r_w) 8760 \, dr_w \right)}{\text{Tariff (\pounds/kWh)}} \times (19)
\]

\[
A_{\text{Loss, Rev}} = \frac{\left( r_{\text{onshore}} \int (P_{\text{losses}}(r_w) + P_{\text{curt}}(r_w)) f(r_w) 8760 \, dr_w \right)}{\text{Tariff (\pounds/kWh)}} \times (20)
\]

The additional housing is estimated to have a 11.5 m diameter base, which is slightly larger compared to the main tower. However, the height (8.5 m) and weight are only a fraction of the main tower. The weight of the housing can be offset against the weight saved from replacing the heavy low frequency transformer (used with AC connection) and therefore the total weight of towers in both cases will be similar.

Following from the cost model, a type 4 AC wind generator costs about 16.423 M\(\pounds\) (including foundation cost, which takes about 51% of the total cost) while a DC wind generator with foundation (excluding the cost of insulating materials and additional housing) costs about 20.49 M\(\pounds\).
of information from manufacturers, exact cost of the insulating materials and additional housing is not readily available. Therefore, in this study, 10% of the DC generator cost is assumed to cater for these items, which makes the total cost of a single DC generator around 22.54 M£.

6 | CASE STUDY

The test system is a 1 GW windfarm with 100 (25 × 4) state-of-the-art 10 MW wind generators, as presented in Table A2 in the Appendix. A maximum of 3% outage is also applied in the windfarm (i.e., three generators out of service within the windfarm with a limitation of one generator per string). The maximum difference in power on wind generators is 50%.

6.1 | Operation at rated HVDC voltage

In this section, the HVDC voltage is set to its nominal value by the onshore converter and generator outages were applied on wind generators WG5_1, WG10_2, and WG15_4 located in strings one, two, and four respectively. The expression in (12) was used to determine the overvoltage coefficient considering just the generator outage \( \alpha_{ov, first} \), which was found to be 1.0417 pu per unit (pu) (corresponding to a generator voltage of 21.876 kV). This corresponds to the case of equal (rated 10 MW) powers on all the generators (obtained for high average wind speeds, around 12 m/s).

Note that this test system will not give rated total power at a mean wind speed equal to rated (i.e., 10.85 m/s), because of the assumed difference in generator power and blade power limiting for power over 10 MW. This is depicted in Figure 5a where powers on all 25 wind generators in string 3 are seen as the wind speed varies and the average rated total power is observed at an average wind speed higher than rated.

6.2 | HVDC voltage control with optimal voltage rating on generator

Here, both generator outage and assumed variation in wind speed are considered to examine the benefit of DC voltage reduction. The operation of the windfarm at a wind speed of 10 m/s is assumed, where high DC voltage stress on generators is expected. Generator outages are maintained on WG5_1, WG10_2, and WG15_4. To determine the optimal DC voltage \( V_{HVDC, opt} \), the DC voltage control in the design algorithm gradually reduces the HVDC voltage from its rated value and the key variables are calculated as depicted in Figure 5b,c considering a case where \( \alpha_{ov} = 1.0417 \) pu. This confirms that the method in [10] (first overvoltage) is inadequate as the power curtailment (red curve on right axis in Figure 5b) at rated voltage is high (76.2 MW), which affects the power delivered onshore (green curve on left axis).

The power delivery is seen to increase as the HVDC voltage reduces, whereby the maximum power delivered (833.6 MW) is achieved at \( V_{HVDC, opt} = 477 \) kV (i.e., the optimal DC voltage level). At this level, the minimum power curtailment is observed (i.e., 0.33 MW). The cable losses on the other hand are seen to increase as the DC voltage reduces, mainly due to the increased string currents as observed in Figure 5c. Further reduction of the DC voltage above \( V_{HVDC, opt} \) increases the power curtailment (from process of maintaining the string currents within their rated levels i.e., 0.4762 kA).

Nevertheless, as observed in Figure 5b, some undesirable curtailment losses are still evident in the system when \( \alpha_{ov, first} \) and \( V_{HVDC, opt} \) are utilized. This is also seen at certain wind speeds as
shown in Figure 5d, where the curtailment losses (brown curve on the left axis) are calculated for each wind speed, with the peak (7.5 MW) observed around 10.2 m/s. The DC voltage control is seen to properly regulate the optimal DC voltage (red curve on the right axis) as the wind speed changes.

The power curtailment issue is resolved by determining the optimal overvoltage coefficient considering the above DC voltage control. This is obtained following the overvoltage coefficient algorithm in Figure 3b. The algorithm varies the wind speed from cut-in ($v_{w,ci}$) to cut-out ($v_{w,co}$) speed and then records the overvoltage coefficients required to avoid curtailment at every instant as shown in Figure 6a. The recommended optimal overvoltage coefficient $\alpha_{ov,\text{opt}}$ here is found to be approximately 1.145 pu (corresponding to an optimal voltage rating of 24.045 kV). As observed in Figure 6b, adopting $\alpha_{ov,\text{opt}}$ avoids curtailment (brown curve on the left axis) at all wind speeds, thereby maximizing power delivery onshore.

On the downside, the DC voltage control varies the transmission voltage up to 25% of the rated voltage and this increases the conduction losses.

Table 1 shows in-depth analysis of benefit of DC voltage control and it is observed that utilizing DC voltage control (with $\alpha_{ov,\text{opt}}$) provides about 141.6 GWh additional energy annually from the windfarm despite the increase in cable and converter losses. The annual energy curtailment losses are 1.79% of total windfarm generation for the solution with no DC control. Avoiding curtailment here will require increasing the overvoltage coefficient, which will adversely affect the initial investment cost since converter costs increase linearly with increased coefficient. This clearly points to the benefits of utilizing $\alpha_{ov,\text{opt}}$ with $V_{HVDC,\text{opt}}$ in terms of cost. The additional financial benefits of DC voltage control are shown in Table 2, where the additional energy translates directly to about 1.7% and 2.2% higher annual revenue and profit, respectively. Also, the proposed solution is seen to improve the NPV by 12.2%, which affirms the profitability of the project.

Some results in Table 2 will change significantly when a higher energy cost is considered. A 50% increase in energy cost will increase the annual revenue and profit by almost the same percentage. However, the NPV will increase by almost 4.5 times while cost of components (CAPEX) remains unchanged.

From the analysis above, it is apparent that utilizing $\alpha_{ov,\text{first}}$ DC voltage control as done in [10] and [14] is not the best design approach for large DC windfarms.

It is evident that the proposed solution offers great benefits to large DC offshore windfarms and can inform the required generator equipment rating in the design stage as well as the benefits to be expected over the lifetime of a project.

6.3 Parameter sensitivity analysis

The sensitivity analysis is carried out to understand how variations in the following parameters affect the optimal overvoltage coefficient:

1. Nominal HVDC voltage. Some of the commonly used voltage levels in the existing offshore windfarm projects (i.e., 640 and 400 kV) were utilized.
2. Number of strings. Three (3) additional numbers of strings (10, 8, and 3) are considered.
3. Difference between the largest and smallest power on generators in the windfarm. Two additional power dispersion levels (30% and 20%) are considered.
4. Maximum number of generators under outage. Two additional generator outage scenarios are considered: 6% and 9%.
TABLE 2  Cost-benefit analysis with and without DC voltage control.

<table>
<thead>
<tr>
<th>DC voltage</th>
<th>Optimal overvoltage coefficient (α_{ov},opt) (pu)</th>
<th>Total investment cost (M£)</th>
<th>O&amp;M cost (M£)</th>
<th>Annual revenue (M£)</th>
<th>Annual profit (M£)</th>
<th>NPV (M£)</th>
<th>Simple payback time (Year. Months)</th>
<th>Annual loss in revenue (M£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed DC voltage</td>
<td>1.145</td>
<td>2,295.1</td>
<td>83.86</td>
<td>374.42</td>
<td>290.56</td>
<td>444.03</td>
<td>7.0</td>
<td>37.68</td>
</tr>
<tr>
<td>Optimal DC voltage</td>
<td>1.145</td>
<td>2,295.1</td>
<td>83.86</td>
<td>380.93</td>
<td>297.07</td>
<td>505.42</td>
<td>7.7</td>
<td>31.17</td>
</tr>
</tbody>
</table>

TABLE 3  Effect of changing design parameters on optimal overvoltage coefficient.

<table>
<thead>
<tr>
<th>Sensitivity parameters</th>
<th>Optimal overvoltage coefficient α_{ov,opt} (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HVDC voltage</td>
</tr>
<tr>
<td>Number of generators and strings (x x y)</td>
<td>640 kV</td>
</tr>
<tr>
<td>50% power dispersion</td>
<td>3% (1 Outage per string)</td>
</tr>
<tr>
<td></td>
<td>6% (2 Outages per string)</td>
</tr>
<tr>
<td></td>
<td>9% (3 Outages per string)</td>
</tr>
<tr>
<td>30% power dispersion</td>
<td>3% (1 Outage per string)</td>
</tr>
<tr>
<td></td>
<td>6% (2 Outages per string)</td>
</tr>
<tr>
<td></td>
<td>9% (3 Outages per string)</td>
</tr>
<tr>
<td>20% power dispersion</td>
<td>3% (1 Outage per string)</td>
</tr>
<tr>
<td></td>
<td>6% (2 Outages per string)</td>
</tr>
<tr>
<td></td>
<td>9% (3 Outages per string)</td>
</tr>
</tbody>
</table>

The results are presented in Table 3, where it can be observed that changing the HVDC voltage level has no impact on the optimal overvoltage coefficient. However, as the power dispersion decreases, the optimal coefficient also decreases, as expected. In practice, this indicates a trade-off between equipment overvoltage and distance between generators. Also, the required overvoltage increases with increased number of generator outages per string since higher voltage/current stresses are exerted on the remaining generators.

For a specific power dispersion, the optimal overvoltage coefficient is seen to increase with reduced number of generators in a string. It is seen that for a power dispersion of 50% and an extreme case of 9% generator outage (i.e., 3 outages per string), the optimal overvoltage coefficient can get as high as 1.57 pu. This demonstrates the benefits of utilizing less strings in a windfarm since this translates to a larger number of series-connected generators. This will also make the cost of the generator equipment and associated components lower, reducing the total investment cost.

On the other hand, one of the key benefits of increasing the number of strings is their availability. In an unexpected event where string failure occurs, the impact on power loss and loss in revenue will be less significant for topologies utilizing multiple strings compared to those with a lower number of strings. Also, component ratings impose a limit on the maximum current in a string.

7  | TIME-DOMAIN SIMULATION ON DETAILED MODEL

The above results are obtained using parametric model in MATLAB with optimization algorithms that are valid in steady-state only. The performance of the series-parallel windfarm test case from Figure 1 with the pre-designed equipment rating (an overvoltage coefficient of 1.145 pu) and DC voltage control is also verified by detailed PSCAD/EMTDC time-domain simulation. MMC is presented as a Type 4 model, and wind generators as controllable power sources, all with nonlinear feedback controls.

7.1  | 50% Generator power dispersion with 3% generator outage

This scenario simulates the functionality of the system under the worst-case wind speed dispersal and generator outage, with results in Figure 7. As seen in Figure 7a, the generator powers at string 1 (similar with strings 2, 3, and 4) were maintained at the rated level (i.e., 10MW) before 2 s. The powers are then dispersed according to the random generation algorithm between 2–5 s.

As predicted in the MATLAB design and shown in Figure 7c, the HVDC voltage control reduces the transmission voltage to 415 kV in order to maximize the delivered power. As a result,
the generator voltages and HVDC current are adjusted accordingly, as seen in Figure 7b, respectively. As shown in Figure 7d, the power delivered onshore (674.6 MW) is reasonably close to the available power (677.6 MW) with small conduction losses.

Generator 11, and other two in strings 2 and 4 (i.e., $P_{g1,1}$, $P_{g12,2}$ and $P_{g4,4}$) were bypassed after 5 s simulating their outages. The power $P_{g1,1}$ drops to 0 MW as shown in Figure 7a, which also applies to $P_{g12,2}$ and $P_{g4,4}$. The new optimal transmission voltage is 408 kV. The operating generators in each string thereby increase their voltages to compensate for one lost generator, as observed in Figure 7b. No power curtailment is observed in the system under both 50% wind dispersion and outage of three generators, which validates the design (voltage rating of 1.145 pu together with DC voltage control). A total of 657.6 MW is delivered onshore, which suggests 17 MW is lost, corresponding to the sum of the three lost generators (black curve on right axis) as shown in Figure 7d.

### 7.2 Case outside of design range with outage of four generators in a single string

This scenario simulates the functionality of the system outside the design assumptions in order to understand the limitations of the method. The generator outage in string 1 was extended to 4 (6 in total) by bypassing three additional generating units (i.e., $P_{g10,1}$, $P_{g21,1}$ and $P_{g25,1}$) after 8 s. The transmission voltage is regulated to 400 kV. This event would require operating generators to increase their voltages in order to compensate for outages, but they reach the rated voltage (1.145 pu) (as shown in Figure 7b) and local controllers do not allow further increases. As a result, the respective generators are seen to curtail their powers as shown in Figure 7a. As power reduces on largest-producing machines, current in the string reduces, leading to increased voltage on all other machines and this string maintains transmission voltage (to avoid tripping) as seen in Figure 7b. A total of 634.6 MW is delivered onshore, which suggests about 0.8 MW is lost to curtailment in addition to the sum of the three lost generators (i.e., 22.2 MW). Therefore, if further generators are out of service, the string will not be disconnected, but curtailment increases (graceful degradation in performance).

When compared with parallel connected DC wind farm, this topology will have lower costs, but suffer from higher losses (further increased because of overvoltage ratings), as with all series connected wind farms [10, 14].

### 8 CONCLUSIONS

This paper studied a systematic design method that determines the optimal generator equipment rating and transmission voltage control in a DC windfarm. This was achieved considering the key design and operational challenges of the series-parallel DC topology.

As illustrated by the MATLAB study, an optimal overvoltage coefficient $\alpha_{ov, opt}$ exists considering DC voltage control. With the proposed solution, for a 1 GW test wind farm an optimal coefficient of 1.145 pu with transmission voltage control avoids curtailment at all wind speeds under given conditions. This is shown to offer about 141.6 GWh additional annual energy delivery comparing with the solution without transmission voltage control. These results are particularly important to wind project developers as they give some insights on the...
profitability of a project and NPV indication. The parameter sensitivity analysis performed points to the credibility of the developed model under a range of key parameter changes. The simulation in PSCAD validates the design and control methods and illustrates the functionality of the proposed solution both within and outside design range. The investigation on generator equipment layout and insulation also shows that with appropriate design methods, DC series-parallel topology can be considered feasible and a possible alternative for achieving a reduced overall footprint for offshore windfarm projects.

AUTHOR CONTRIBUTIONS
Ibrahim Ahmad Shehu: Conceptualization; investigation; methodology; validation; writing—original draft; writing—review and editing. Dragan Jovcic: Conceptualization; supervision; validation; visualization; writing—review and editing. Peng Li: Conceptualization; supervision; validation; visualization; writing—review and editing.

ACKNOWLEDGEMENTS
The authors are grateful for the financial support from the Nigerian Petroleum Technology Development Fund (PTDF).

CONFLICT OF INTEREST STATEMENT
The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES
**APPENDIX**

**TABLE A1** Cost parameters.

<table>
<thead>
<tr>
<th>Description</th>
<th>Label</th>
<th>Value/Unit</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid interface cost</td>
<td>$C_{GI}$</td>
<td>75 k€</td>
<td>[25]</td>
</tr>
<tr>
<td>Project Development cost</td>
<td>$C_{PD}$</td>
<td>2%</td>
<td>[25]</td>
</tr>
<tr>
<td>Tariff</td>
<td>-</td>
<td>0.046€/kWh</td>
<td>[32]</td>
</tr>
<tr>
<td>Discount rate</td>
<td>$r$</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>Project period</td>
<td>$T$</td>
<td>30 years</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE A2** Windfarm base case parameters.

<table>
<thead>
<tr>
<th>Description</th>
<th>Label</th>
<th>Value/Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal windfarm power</td>
<td>$P_{WPF}$</td>
<td>1000 MW</td>
</tr>
<tr>
<td>Nominal HVDC voltage</td>
<td>$V_{HVDCnom}$</td>
<td>525 kV</td>
</tr>
<tr>
<td>Number of generators in a string</td>
<td>$x$</td>
<td>25</td>
</tr>
<tr>
<td>Number of strings</td>
<td>$y$</td>
<td>4</td>
</tr>
<tr>
<td>Total number of wind generators in the windfarm</td>
<td>$N_{wt}$</td>
<td>100</td>
</tr>
<tr>
<td>Nominal HVDC current</td>
<td>$I_{HVDC}$</td>
<td>1.905 kA</td>
</tr>
<tr>
<td>Rated generator power</td>
<td>$P_{gr}$</td>
<td>10 MW</td>
</tr>
<tr>
<td>Nominal DC/DC converter output voltage</td>
<td>$V_{dci, nom}$</td>
<td>21 kV</td>
</tr>
<tr>
<td>Nominal DC/DC converter current</td>
<td>$I_{string, nom}$</td>
<td>0.4762 kA</td>
</tr>
<tr>
<td>Maximum number of generator outage per string</td>
<td>$F_i$</td>
<td>1</td>
</tr>
<tr>
<td>Maximum generator outage allowed in windfarm</td>
<td>$F_{max}$</td>
<td>3%</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>$D$</td>
<td>90 m</td>
</tr>
<tr>
<td>Distance between two generators in a string (5 × rotor diameter)</td>
<td>$X_{Gen}$</td>
<td>0.9 km</td>
</tr>
<tr>
<td>Distance between two strings (5 × rotor diameter)</td>
<td>$X_{string}$</td>
<td>0.9 km</td>
</tr>
<tr>
<td>Transmission cable length</td>
<td>-</td>
<td>150 km</td>
</tr>
<tr>
<td>Rated wind speed</td>
<td>$v_{w, r}$</td>
<td>10.845 m/s</td>
</tr>
<tr>
<td>Cut-in wind speed</td>
<td>$v_{w, ci}$</td>
<td>4 m/s</td>
</tr>
<tr>
<td>Cut-out wind speed</td>
<td>$v_{w, co}$</td>
<td>25 m/s</td>
</tr>
<tr>
<td>Capacity factor</td>
<td>$CF$</td>
<td>50%</td>
</tr>
</tbody>
</table>