Formulation of a wind farm control strategy considering lifetime of DC-link capacitor bank of type IV wind turbines

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Abstract
The cost of energy should be minimised to increase market penetration of wind energy conversion systems. The existing wind farm control strategies are not helpful since they speed up the damage in upstream wind turbines. Therefore, a control strategy is proposed to maximise the energy yield while equalising lifetime of one of the most fragile sub-system of the wind turbines. The DC-link capacitor bank of the back-to-back converters is considered to this end. The proposed control strategy can be directly applied in systems based on type 4 wind turbines with full power converters. This exposition reveals the formulation of the control strategy by analysing the strengths and weaknesses of the existing strategies based on the maximum power output. The lifetime-based control strategy is extended to formulate a multi-stage reactive power dispatch method with the help of a total energy-based strategy. The effectiveness of all control strategies is validated using the model-based simulations.

1 | INTRODUCTION

There is a growing demand for wind energy conversion systems based on wind farms because of the relatively low cost of energy (CoE) [1]. The market penetration can be further increased by maximising the energy yield before the first failure since CoE is a function of maintenance cost in addition to the design, installation, and disposal costs. To this end, overcoming the challenges due to the complex interactions between the wind stream and turbines of the on- and off-shore farms are mandatory. This challenge is further intensified by the complex and irregular layouts. Layout of the on-shore wind farm can be optimised at the design stage, although it is challenging for the off-shore applications due to the cost constraints [2]. Therefore, optimised wind farm control strategies become the ultimate solution to maximise instantaneous power while minimising the damage of the electrical systems [3].

The wake, a result of the aerodynamic interaction between the rotor and the wind stream, reduces energy captured by downstream wind turbines while creating increased fatigue loads [4]. The adverse effects of the wake should be minimised to reduce the CoE of wind farms. The existing control strategies and design approaches are based on the total power maximisation [5–10] and they do not guarantee the reduced CoE as discussed in [3]. Therefore, the control strategies targeting energy yield and lifetime of the system are useful. As a solution, wind farm control strategies based on total power and lifetime have been proposed in [4], [12]. The lifetime has been estimated using fatigue load in [4] and the power converter in [12]. The above methods are based on the offline calculations to determine the control parameters under given mission and loading profiles. The mission profile provides the operating conditions of the power converter (temperature, wind speed and humidity), and loading profile provides voltage, current, and data related to the electrical distortions. Both mission and loading profiles are necessary to predict the lifetime of a component of a power conversion system since they jointly decide damage the under a given operating condition [13]. Moreover, a wind turbine de-rating strategy has been proposed to extend the life of wind turbines in [14] considering damage of power converters. Application of the proposed method to optimise the performance of a wind farm has not been demonstrated. Furthermore, control strategies to support ancillary function such as reactive power dispatch have been discussed in [12, 15, 16]. Strategy illustrated in [15] only considers an optimal power dispatch method without considering the CoE. The strategies

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The type 4 wind turbines are useful in this context since they compensate reactive power while concealing the turbine and generator in the fault conditions. To formulate control strategies addressing these requirements, suitable engineering models are used although they do not characterise complex static and dynamic properties of the wind field, turbines and the power converters. These models can be fed by the extracted data from the mission profile to estimate the instantaneous operating condition of the wind turbines. The instantaneous operating conditions can be optimised using a coordinated control strategy to minimise the CoE. The simple engineering models would be useful to maximise the output of large wind farms due to the minimum data processing requirements. This approach complements by the existing controller platforms based on the field-programmable gate array (FPGA) and digital signal processor (DSP) and due to the fact of the very low sampling frequency of the supervisory control and data acquisition (SCADA) data. However, the coordinated control system requires good communication infrastructure along with a suitable network of the meteorological masts.

A detailed description of the wind turbine, wind field (wake and wake interaction) and the DC-link capacitor bank of the power converter are provided in Section 2. The cost functions of the two conventional (strategies 1 and 2) and the two newly proposed (strategies 3 and 4) control strategies are presented in Section 3 of this article. The effectiveness of each strategy to maximise the energy yield and to equalise the lifetime is compared in Section 4 using simulation results. Comparison results are used to devise a method to dispatch reactive power demand. The proposed reactive power dispatch method is introduced, and its effectiveness is validated in the fifth section. Therefore, contributions of this article can be summarised as follows,

- Propose a control strategy to minimise the damage of the DC-link capacitor bank of the power converters using suitable cost function while equalising their lifetime.
- Demonstrate the workflow of the proposed method implementation using the data available in wind turbine SCADA data set.
- Extend the proposed method to distribute reactive power demand using energy and lifetime based control strategies.

The proposed methods should be able to implement on existing platforms (SCADA) without using additional sensors and data acquisitions units to minimise the cost.
2 | SYSTEM CHARACTERISATION

The elements of a wind farm are characterised using suitable engineering models, as explained in the following subsections. Each model is closely analysed to identify the required data to feed as the mission and the loading profiles. SCADA data sets of wind turbines are analysed to find a common data set that matches with those models. As a result, wind speed and nacelle temperature are identified as the mission profiles and phase current and voltage, and the reactive power as loading profiles. Moreover, the sampling frequency of the SCADA data set is important to decide the operating frequency of the control strategy and to minimise stresses on the system. Performance of the control strategy significantly affects the sampling frequency of the data since rapid variations in the environmental conditions can be expected at different locations. Influence of the sampling frequency on the system performance has been discussed in [14]. When formulating the proposed control strategy, it is assumed that power converter has additional DC-link voltage control methods under the grid fault conditions as discussed in [21]. It is also assumed that the grid code of the connected system guarantees these faults are cleared within short time compared to the lifetime of the capacitor bank.

2.1 | Wind turbine model

The wind turbines of the farm are modelled considering their energy conversion. The wind speed profile \( V_i \) is fed into the \( i \)th turbine model to estimate the energy converted \( P_{g_i}(\alpha_i) \) by the blades as given by (1); where \( \rho \) is the air density, \( A \) is the rotor cross-sectional area, \( C_p(\alpha_i) \) is the power coefficient. The energy converted by the power converter \( P_{c_i}(\alpha_i) \) is obtained using the energy transfer efficiency \( (\eta) \) between the rotor blades and the power converter. The thrust coefficient \( (C_t) \) could be used instead of the \( C_p \), as defined in (2). The both \( C_p \) and \( C_t \) are functions of the yaw angle \( (\gamma) \) of the rotor and axial induction factor \( (\alpha) \). The \( \alpha \) is a function of torque of the generator and the rotational speed. Moreover, the \( \alpha \) is employed to estimate the pitch angle \( (\beta) \), tip-speed-ratio (TSR) or \( \gamma \) because \( C_p \) is a function of them [7]. Therefore, the \( \alpha \) is selected as one of the control parameters of the proposed control strategies assuming \( \gamma = 0 \).

\[
P_{g_i}(\alpha_i) = \frac{1}{2} \rho A C_p(\alpha_i) V_i^3; P_{c_i}(\alpha_i) = P_{g_i}(\alpha_i) \eta \tag{1}
\]

\[
C_p(\alpha, \gamma) = 4\alpha (\cos(\gamma) - \alpha)^2 \tag{2}
\]

The lifetime of a power converter can be estimated using the \( P_{c_i}(\alpha_i) \) under given operating conditions. The operating conditions are available as the loading and mission profiles of the wind turbines. The lifetime of a power converter is a function of the lifetime of the semiconductor and the passive devices. The most unreliable component of the power converter is assessed to estimate life consumption since the overall power converter considered as a series system in the reliability perspective [22]. The lifetime of the power semiconductor and DC-link capacitors under the same mission profiles are evaluated in PV application in [14] and modular multi-level converters in [23]. Both studies revealed that under similar mission profiles DC-link capacitor is the most prone-to-fail devices. Hence, the DC-link capacitor bank of a back-to-back power converter is evaluated to obtain a reasonable estimation [24]. The previous studies have shown that reliability of the electrolytic capacitors affected by the ambient conditions (such as nacelle temperature) besides the current ripple they are exposed.

2.2 | Damage estimation of the capacitor bank

The DC-link capacitance \( (C_{DC}) \) given by (3) is determined considering the energy balance under the transients [25]; where \( T_r \) is response time of the voltage control loop, \( \Delta P_{max} \) is expected maximum variation in the output power, \( V_{DC} \) is the DC-link voltage and the \( \Delta V_{DC,max} \) is the DC-link voltage amplitude. A large capacitance is required to fulfill the rapid power fluctuations that can be realised using Aluminum electrolytic capacitors. However, a single element does not provide the required capacitance due to the available capacitors and their voltage ratings. Hence, the capacitance is obtained using series and parallel connected capacitor bank having comparably lower reliability compared to a single capacitor under the applicable mission and loading profiles, as discussed in [24]. The stresses on the capacitor bank are not only due to the rapid variations in the wind profile but also due to the variations in ambient temperature.

\[
C_{DC} \geq \frac{T_r \Delta P_{max}}{2V_{DC} \Delta V_{DC,max}} \tag{3}
\]

The lifetime of an electrolytic capacitor is estimated using its mission and loading profiles. The ambient temperature and energy processed by the DC-link capacitor are considered as the mission and the loading profiles, respectively. The nacelle temperature of the data set is used as the ambient temperature. The damage due to the energy processed by the DC-link capacitor is calculated using the root mean square (RMS) of the harmonic currents \( (I_c) \). The RMS value of the fundamental component of the DC-link capacitor current is approximated using (4) [26]; where \( M \) is the modulation index of the grid-connected converter, \( I_p \) is the RMS phase current, and \( \phi \) is the displacement angle. The \( I_p \) and \( \phi \) is obtained from the SCADA data set and the \( M \) depends on the power modulation method employed in the grid-connected power converter. A relationship between the \( M \) and \( \phi \) is obtained using the method proposed in [27].

\[
I_c = I_p \sqrt{2M \left( \frac{\sqrt{3}}{4\pi} + \cos^2 \phi \left( \frac{\sqrt{3}}{\pi} - \frac{9M}{16} \right) \right)} \tag{4}
\]
The total power dissipation \( P_{\text{core},x} \) in the DC-link capacitor due to the equivalent series resistance (ESR) \( r_x \) at all harmonic frequencies \( f_x \) is given by (5). The ESR is frequency and temperature dependent, and those values are available in capacitor data sheets [28]. The RMS value of the all harmonics can be obtained using the methods as discussed in [28], when the required data available having sufficient resolution. However, SCADA data set just provides RMS value of each phase current sampled at very low frequency. Therefore, in this analysis, only the fundamental component of the DC-link capacitor current is considered to estimate internal power dissipation. Hence, the power dissipation in the capacitor core \( P_{\text{core}} \) is given by (5).

\[
P_{\text{core},x} = \sum_{f_x} I_{x}^2 r_x, \quad P_{\text{core}} = \sum_{f_x} I_{x}^2 r_1 \tag{5}
\]

The core temperature \( T_{\text{core}} \) of the DC-link capacitor is obtained by considering the equivalent electrical model of the capacitor as shown in Figure 2; where \( R_{\text{ct}} \) is core-to-case thermal resistance and \( R_{\text{ta}} \) is case-to-ambient thermal resistance, \( T_t \) is the case temperature and \( T_a \) is the ambient temperature. Therefore, the core temperature \( T_{\text{core}} \) of the DC-link capacitor is given by (6) [31]. The \( R_{\text{ct}} \) and \( R_{\text{ta}} \) are obtained from a capacitor datasheet, in the analysis. The model does not contain a thermal capacitance since only the steady-state conditions of the thermal circuit are taken into consideration. Therefore, the sampling frequency for the mission and loading profile is selected at a lower value compared to the thermal time constant of the capacitor to eliminate inconsistencies between the results and the actual behaviour of the thermal circuit.

\[
T_{\text{core}} = T_a + P_{\text{core}} \left( R_{\text{ct}} + R_{\text{ta}} \right) \tag{6}
\]

The estimated core temperature \( T_{\text{core}} \) is employed to approximate lifetime of the capacitor \( L_x \) under a certain stress level using (7); where \( V_{\text{ct}} \) is the applied DC voltage, \( V_{\text{r}} \) is the rated DC voltage, \( T_{\text{max}} \) is the maximum permissible core temperature and \( T_{\text{core}} \) is actual core temperature and \( L_x \) is the nominal lifetime of the capacitor at \( T_{\text{max}} \), which is obtained from the data sheet of the capacitor [32]. The selected lifetime model explains wear out in the capacitor due to electrolyte evaporation and electro-chemical reactions. The major stressors behind these failures are ambient temperature, voltage and current ripples of the capacitors. However, the model does not explain random failures that can expect within the life span of a capacitor. Moreover, wear out best explains the lifetime of a capacitor in the bank rather than an individual unit. Hence, the selected model is the best choice to explains the behaviour of the DC-link capacitor.

\[
L_x = L_0 \left( 4.3 - 3.3 \times \frac{V_{\text{ct}}}{V_{\text{r}}} \right)^2; \quad \tau = \frac{T_{\text{max}} - T_{\text{core}}}{10} \tag{7}
\]

The damage in the capacitor under a given mission profile is obtained using Miner’s rule as in (9); where \( \xi \) is the number of cycles at a certain stress level \( (\xi) \) which can be obtained by the sampling time of the data set. The \( L_x \) is the number of cycles to failure calculated at that stress level which is given by (8). The lifetime of the capacitor \( L_{x,\text{tot}} \) is calculated using (9) when total damage accumulates to 1 and it is given by

\[
L_{x,\text{tot}} = \frac{1}{D} \tag{8}
\]

\[
D = \sum_{i=1}^{n} \frac{\xi_i}{L_x} \tag{9}
\]

### 2.3 Wake modelling of the wind farm

The complex interaction between the wind stream and the rotor blades deforms wind stream. The characterisation of the aggregated effect of deformation on a turbine in multi-turbine setup is a complex task. Therefore, aggregated wind speed at a given wind turbine is obtained using a suitable model rather than characterising complete wind speed profile. Therefore, Park wake model [33] is applied to obtain the wind speed at a downstream wind turbine as given by (10); where \( V_i \) and \( A_i \) are the wind speed and the rotor area of the \( i \)th wind turbine, \( N \) is the number of the wind turbines, \( \delta \) is the surface roughness factor, \( \alpha_i \) and \( D_i \) are the axial induction factor and the diameter of the \( i \)th wind turbine, \( \delta \) is the surface roughness factor, \( \alpha_i \) and \( D_i \) are the separation and rotor area overlap between the \( j \)th and \( i \)th wind turbines. The roughness factor \( \delta \) defines the slope at which the wake expands out from the turbine. Roughness coefficients have been found empirically for many different environments, \( \delta = 0.075 \) for land cases and \( \delta = 0.04 \) for offshore locations. The surface roughness factors cause significant reduction in wind speed and substantial increase in turbulence intensity, as explained in [34]. The rotor area overlap can be obtained using the method explained in [33]. The \( V_{\infty} \) is the

![Figure 2](image-url)
upcoming wind speed.

\[ V_i = V_\infty \left( 1 - 2 \sqrt{\sum_{j} (\alpha_j)} \right)^2 \]

\[ C_{ji} = \left( \frac{D_j}{D_j + 2\delta (x_i - x_j)} \right)^2 \left( \frac{A_{\text{overlap}}}{A_i} \right) \] (10)

3 THE ANALYSED CONTROL STRATEGIES

Estimating the axial induction factor \((\alpha_i)\) of each wind turbine and the dispatch of the active and reactive power demand are the key functionalities of a wind farm control strategy. The control strategy should perform these functions while minimising the damage before the first failure. Figure 3 shows the selected workflow to achieve the above objectives. The two major inputs of the workflow are the wind speed \((V_\infty)\) and the nacelle temperature \((T_a)\), and they are provided as vectors, as shown in Figure 3. Apart from that, the parameters of each sub-system are provided as the hard-coded inputs. For an example, rotor diameter \((D_j)\), the distance between the wind turbines \((x_i - x_j)\) as a function of the rotor diameter and the surface roughness factor \((\delta)\) are the inputs to the wake model, air density \((\rho)\) is an input to the turbine model. The inputs of the capacitor model are defined in (4), (5) and (6) and the capacitor lifetime model is in (7). Analysed four control strategies are also shown in Figure 3 and a detailed description of each strategy is provided in following sections along with their cost function.

3.1 Strategy 1 – MPPT of individual turbine

In this conventional strategy, each wind turbine is operated at its maximum power point without considering the power converter control command and the lifetime, as shown in Figure 3. Therefore, all turbines are operated at \(\alpha_i = 0.33\), although this assumption is not valid for wind speeds higher than the rated value in real applications. Lifetime of the DC-link capacitor bank of each power converter \((L_{w,i})\) is calculated using the constant \(\alpha_i\) vector to estimate the total energy yield \((E_{t,1})\) as in (11b). This control strategy can be implemented inside each turbine and it is not required to have a communication infrastructure among turbines and a central controller. However, it will create more disturbance in the wind stream.

\[ \alpha_i = 0.33 \forall i \in N \] (11a)

\[ E_{t,1} = \sum_{i=1}^{N} P_{c,i}(\alpha_i)L_{w,i} \] (11b)

3.2 Strategy 2 – maximum power of wind farm

The objective of this control strategy is to maximise the total power \((P_{t,2})\) of the wind farm. The cost function given by (12a) is maximised to obtain the \(\alpha_i\) vector which satisfies that condition. Lifetime of the DC-link capacitor bank of each power converter \((L_{w,i})\) under a given mission and loading profile is estimated using \(\alpha_i\) vector, as shown in Figure 3. The total energy yield \((E_{t,2})\) is calculated using (12b). The implementation of this strategy is based on a central controller. Hence, the performance of the system depending on the reliability of the communication network.

\[ \text{max} P_{t,2} = \sum_{i=1}^{N} P_{c,i}(\alpha_i)0 < \alpha_i < 1 \] (12a)

\[ E_{t,2} = \sum_{i=1}^{N} P_{c,i}(\alpha_i)L_{w,i} \] (12b)

3.3 Strategy 3 – maximum energy yield

The cost function of this control strategy maximises the total energy yield of the wind farm. The \(\alpha_i\) vector satisfies the conditions stipulated in (13a) is employed to estimate the lifetime vector of the DC-link capacitor bank of wind turbines. The total energy yield \((E_{t,3})\) is estimated using the lifetime vector, as shown in Figure 3 using (13b). The energy yield of a farm can be maximised either increasing the power extraction or lifetime of the converters. As a result, it is expected to
minimise the damage of the upstream turbines using this strategy. Moreover, the maximised energy yield helps reduce the cost of energy. To achieve this objective, there should be a reliable communication link between the central controller and wind turbines.

$$\text{max} E_t = \sum_{i=1}^{N} P_{r,i} (\alpha_i) L_{w,i} 0 < \alpha_i < 1$$ \hspace{1cm} (13a)

$$E_{t,\alpha} = \sum_{i=1}^{N} P_{r,i} (\alpha_i) L_{w,i}$$ \hspace{1cm} (13b)

### 3.4 Strategy 4 – equal life span

The objective of this control strategy is to equalise the lifespan of DC-link capacitor bank of the power converters. Lifetime function ($L_{eq}$) is minimised to obtain the $\alpha_i$ vector defined in (14b) using the average lifetime ($L_\alpha$) in (14a). The average lifetime ($L_\alpha$) is calculated in (14a) using the $\alpha_i$ vector at a particular operating condition. The total energy yield ($E_{t,\alpha}$) of the wind farm with this control strategy is estimated using the $\alpha_i$ and $L_{w,i}$ vectors. The basic idea behind formulation of the cost function is to minimise difference between lifetime of capacitor bank in each wind turbines($L_{w,i}$). To this end, difference between the $L_\alpha$ and $L_{w,i}$ is taken into consideration. The square term of difference is evaluated to increase the significance between the $\alpha_i$ vector. The optimisation function helps find $\alpha_i$ vector which gives rise the lowest $L_{eq}$. A similar cost function can be formulated considering lifetime difference between two capacitor banks. It demands for more computation power since number of combinations to consider increases with the turbine count. Moreover, the cost function helps eliminate parameter tuning problem when it is formulated as a linear combination of $L_{w,i}$. The equal life span strategy might useful in real-world applications to minimise operation and maintenance cost. However, the required computation power to estimate the parameters real-time is a little high and can be fulfilled using the existing FPGA and DSP.

$$L_\alpha = \frac{1}{N} \sum_{i=1}^{N} L_{w,i}$$ \hspace{1cm} (14a)

$$\text{min} L_{eq} = \sum_{i=1}^{N} (L_\alpha - L_{w,i})^2$$ \hspace{1cm} (14b)

$$E_{t,\alpha} = \sum_{i=1}^{N} P_{r,i} (\alpha_i) L_{w,i}$$ \hspace{1cm} (14c)

The accuracy of the wind speed prediction and the time resolution is important to obtain accurate output using these control strategies. Both control strategies 1 and 2 are not depending on the capacitor bank lifetime since the cost function only based on power. Moreover, both control strategies do not consider either active and reactive power demand along with the converter parameters. As a result, they are not useful to formulate a strategy to dispatch control command provided by the utility grid. However, they can be combined with either strategies 3 or 4 to decide axial induction factors ($\alpha_j$) to dispatch the reactive power demand. With either control strategy, the searching for the optimal $\alpha_j$ vector has been performed within the constraints of $C_p$ and $C_q$ specified by (2).

### 4 CASE STUDY

A wind farm having a line formation (as a motivational example) is analysed to test the effectiveness of the four control strategies. It is assumed that there is a wind stream in parallel to the rotor axis. A parallel wind stream to the axis of the turbines is considered to analyse the worst-case scenario. Here, all the downstream wind turbines are within the wake shadow of all upstream wind turbines. But when wind stream is not parallel to the rotor axis, some of the downstream wind turbines may not within wake shadow of the upstream wind turbine. As a result, wind speed deficit will lower than the previous case. In this study, our focus is to minimise the damage of the wind turbine under the worst case. The Jensen wake model is powerful enough to estimate the wind speed under these conditions. A detailed description of this approach can be found in [2]. Sensitivity analysis in [4] has shown that change in wind speed has a higher impact on the power extraction of wind farm compared to its change in the direction. The separation between wind turbines ($x_j-x_i$) is defined as a function of the rotor diameter, as shown in Figure 4. The spacing is varied to test the performance of the wind farm under the dense turbine spacing. The parameters of the analysed system are listed in Table 1. They are selected to have 18.81 years lifetime when $T_c = 28^\circ C$, $V_\infty = 12 \text{m/s}$ and $\alpha_i = 0.33$. The formulated bounded optimisation problems are solved using the sequential quadratic programming (SQP) algorithm [35]. The initial conditions ($V^i$ and $\alpha_0$) of the algorithm are defined considering the lower ($\alpha_j = 0$) and upper ($\alpha_j = 1$) bounds of the axial induction factor ($\alpha_j$). The SQP algorithm finds a local/global optimum point of each cost function within the constraints in each iteration step. More details about the SQP algorithm can be found in [35]. The cost functions are optimised considering the relationship between the active and reactive power dispatch defined by the function $h$ according to the grid code; where $Q_r$ is total reactive power.

![Figure 4](image_url)
### Table 1
Parameters of the wind farm, turbines, and DC-link capacitor bank

| Parameter                        | Value          |
|----------------------------------|----------------|
| Wind farm                        |                |
| Surface roughness factor ($\delta$) | 0.075          |
| Air density ($\rho$)              | 1.125 kgm$^{-3}$ |
| Wind turbine                     |                |
| Diameter                         | 60 m           |
| Rotor to converter efficiency    | 80%            |
| Power converter                  |                |
| Number of parallel converters    | 6              |
| DC-link capacitor bank           | 7 parallel branches |
| DC-link capacitor                | 3300 $\mu$F/500 V |
| Endurance life                   | 5000 h @ 85°C  |
| ESR of a capacitor               | 48 mΩ          |
| Core-to-case thermal resistance  | 0.32 W/$^\circ$C |
| Case-to-ambient thermal resistance| 0.91 W/$^\circ$C |
| Grid voltage                     | 690 V          |

**FIGURE 5** Rotor axial induction factor of each wind turbine at different wind speeds when turbine spacing is 8D and the wake-rotor interaction is 100% demand. $P_t$ is total active power and $Q_{\text{ref}}$ is the ratio between the $P_t$ and $Q_t$.

**Minimise or maximise**

$P_{1,2}$ or $E_t$ or $I_{\text{eq}}$

**Subject to:**

$0 < \alpha < 1$

**Constraints:**

$b = Q_t - P_t; Q_{\text{ref}}$

**Input:**

$V_t = [8, 9, 10...16]$

$\alpha_0 = [0, 0, 0, 0, 0]$

All the simulations are performed assuming there is 100% wake-rotor interaction for the worst-case analysis. Figure 5 shows the obtained rotor axial induction factors ($\alpha$) using control strategies 2, 3, and 4 at different wind speeds. The $\alpha$s of each wind turbine at considered wind speeds are at constant values with control strategies 1 and 2. The upstream wind turbine has a higher $\alpha$ to extract more energy using strategy 2 since it is based on maximum power. The second wind turbine operates at the lowest $\alpha$, at all wind speeds with the same strategy and gradually increase to reaches the highest value at the fifth row. However, $\alpha_t$ obtained using Strategy 3 at the fifth row is lowest at the high wind speed, since it tries to maximise the energy yield maximising lifetime of capacitor bank. As a result, there is almost equal wind speed at the downstream wind turbines, as shown in Figure 6. There is a significant variation in $\alpha_t$ at a given row with the control strategy 3, specifically at vicinity of the rated wind speed. This variation is significant in rows 1 and 2 compared to the remaining rows. As a result, a significant reduction in wind speed shows at the vicinity of rated wind speed with the control strategy 3, as shown in Figure 6. Figure 6 shows a significant reduction in the speed at all incoming wind with the control strategy 4. This is a result of the gradual increase in $\alpha_t$ when it goes down along the turbine columns at all wind speeds, as shown in Figure 5. As a result, strategies 2 and 3 help extract more power at wind speeds up to 15 ms$^{-1}$, as shown in Figure 7(a). Moreover, Figure 7(a) shows that power extraction with the control strategy 3 starts to decline after certain wind speed although it gradually increases with strategy 4. These trends are quantitatively illustrated in Figure 7(b) normalised power gain with respect to strategy 2. Initially, there is 24.76% power gain difference between the strategies 2 and 4, although there is no big difference in value, as shown in Table 2. The power gain difference between the strategies 2 and 3 reaches 15.21% at higher wind speeds (16 ms$^{-1}$) although it is negligible at wind speeds below the rated value.
### Table 2: Performance comparison of the simulated system at different wind speeds when there are 8D and 4D spacing with the four control strategies

| Spacing | Wind speed | Parameter | Strategy 1 | Strategy 2 | Strategy 3 | Strategy 4 |
|---------|------------|-----------|-----------|-----------|-----------|-----------|
|         | 8 ms⁻¹     | Power (MW) | 1.345     | 1.408     | 1.408     | 1.06      |
|         | 8 ms⁻¹     | Energy yield (TWh) | 0.2764 | 0.2894 | 0.2894 | 0.219 |
|         | 8 ms⁻¹     | Lifetime (years) - upstream | 23.26 | 23.3 | 23.3 | 23.59 |
| 8D      | 12 ms⁻¹    | Power (MW) | 4.539     | 4.753     | 4.575     | 3.919     |
|         | 12 ms⁻¹    | Energy yield (TWh) | 0.8298 | 0.8657 | 0.8668 | 0.7492 |
|         | 12 ms⁻¹    | Lifetime (years) - upstream | 18.81 | 19.18 | 19.5 | 21.82 |
| 4D      | 16 ms⁻¹    | Power (MW) | 10.76     | 11.27     | 9.535     | 9.816     |
|         | 16 ms⁻¹    | Energy yield (TWh) | 1.137 | 1.142 | 1.205 | 1.204 |
|         | 16 ms⁻¹    | Lifetime (years) - upstream | 6.429 | 7.164 | 14.4 | 14.0 |

![Figure 8](image)

**FIGURE 8** The energy yield at different wind speeds when there is 8D turbine spacing and 100% wake-rotor interaction (a) with four control strategies, (b) gain comparison among the strategies, when there is 8D spacing and 100% wake-rotor interaction

Figure 8(a) shows the total energy yield at different wind speeds with the four control strategies. There is no significant difference in energy yield between the control strategies 2 and 3 up to the rated wind speed, as shown in Figure 8(a,b) as similar to the power extraction. After the rated wind speed, the difference starts to increase from 0.12% to 5.2%. Moreover, the energy yield of the control strategy 4 is significantly low at the lower wind speeds compared to the rated value, although it is comparably high at the higher wind speeds, as shown in Figure 8(b). However, the energy yield of strategy 4 is high as strategy 3 at the wind speed 16 ms⁻¹. On the other hand, strategy 3 gives higher energy yield at all wind speeds as expected, and power output very similar to the strategy 2 which is based on maximum power output up to 12 ms⁻¹.

The resultant lifetime vectors of the DC-link capacitor bank of each wind turbine at different wind speeds are shown in Figure 9. The DC-link capacitor bank lifetime of the upstream wind turbine is significantly lower with the control strategies 1, 2, and 3. However, wind turbine lifetime with the control strategy 3 is much better when consider the upstream wind turbine. Most importantly, the DC-link capacitor bank lifetime can be balanced using the control strategy 4, although there is a small increase in the capacitor bank lifetime at lower wind speeds. However, there is a equalised and increased lifetime at higher wind speeds. Also, Table 2 shows that strategy 4 increases the lifetime of the DC-link capacitor bank at any wind speed even under the dense spacing.

The effectiveness of the control strategies 3 and 4 in the wind farms where there is a dense spacing is evaluated using the total energy yield, extracted power and the lifetime. The strategies 1 and 2 are not considered further due to the significant damage in the upstream wind turbines. The selected control strategies (3 and 4) are tested at the turbine spacing 6D and 4D. Figure 10 shows the lifetime before the first failure, the extracted power and the total energy yield. Figures 10(a, b, e, f) and Table 2 show an increase in the DC-link capacitor bank lifetime at all wind speed with both control strategies. However, there is a significant reduction in the total energy yield, as shown in Figure 10(c, d, g, h) due to the low power extraction as shown by the data in Table 2. Also, the trends shown in Figure 10(d, h) show that control strategies 3 and 4 harvests more energy when there is increasing turbine density even at higher wind speeds.

In addition to that, the outcomes of the control strategies 3 and 4 can be compared with the results generated using the method proposed in [4]. The estimated captured power using the control strategies based on the MPP of a wind turbine, MPP whole wind farm and fatigue load has a similar trend, as shown...
The DC-link capacitor bank lifetime (years) before the first failure at different wind speeds, (a) strategy 1, (b) strategy 2, (c) strategy 3, and (d) strategy 4.

Effectiveness of the control strategies 3 and 4 are evaluated at turbine spacing (a, b, c, d) 6D, and (e, f, g, h) 4D where there is 100% wake rotor interaction. (a, e, b, f) The DC-link capacitor bank lifetime with strategy 3 and 4. (c, d, g, h) The power extraction and the total energy yield with the control strategies 3 and 4.

ANCILLARY FUNCTION SUPPORT

The wind farm should support ancillary functions such as reactive power compensation. The expected reactive power handling capability is specified in grid codes [20], and it should be distributed among generators by the supervisory controller. The assigned additional load increases the total load on a power converter of the wind turbine. The increased load gives rise higher damage in the power converter. The DC-link capacitor bank of a converter plays key role in reactive power compensation. As a result, the electrolytic capacitor bank is the most affected components in the system. Hence, the supervisory controller of the wind farm should have a strategy to dispatch total reactive power demand while minimising damage to the converters, as explained in [16]. It is important when system experiences low-voltage voltage ride through satisfying the grid codes. The additional mechanisms incorporated into the DC-link [21] protect capacitor bank from experiencing overrated voltages even during these random scenarios. The control strategies proposed in Section 4 should be able to use in this application since they are based on the damage of the capacitor bank. Usefulness of the control strategies 3 and 4 to formulate a reactive power dispatch strategy is investigated in this section.

Figure 11 shows the formulated two-stage control strategy to dispatch the reactive power demand. The $\alpha_i$ of each wind turbine is decided at the first step assuming zero reactive power demand ($Q_{\text{ref}} = 0$). Also, it is assumed that the modulation index of each wind turbine is at its nominal value ($M = 1$). The cost functions of strategies 3 and 4 are optimised within the constraints defined by (2) to obtain the $\alpha_i$ vector. The resultant $\alpha_i$ vector is used along with the wind speed ($V_i$) and temperatures ($T_a$) to dispatch the total reactive power demand in step.
The total reactive power demand is defined as a percentage of the active power, and it is selected as 0.4 in the case study. The reactive power handled by each wind turbine is defined using the active power handled by each wind turbine, and their displacement angles. The optimisation algorithm is used to get a reactive power vector based on the employed strategy. The total energy yield when the $\alpha_i$ vector is obtained using strategy 3 and reactive power is dispatched using strategies 3 and 4 are shown in Figure 12(a). Figure 12(b, c) shows the damage vectors at different wind speeds with strategy 4 and strategy 3, respectively. A similar set of graphs are shown in Figure 12(d–f) when the $\alpha_i$ vector is obtained using strategy 4. Strategy 4 helps balance the DC-link capacitor bank lifetime compared to strategy 3, although it has comparably low energy yield around and above the rated wind speed. The observations obtained using the analysis are summarised in Table 3. Table 3 shows that there is higher energy yield when $\alpha_i$ vector is obtained using strategy 3 and dispatch the reactive power using strategy 4 which is equal to 0.8655 and 1.197 TWh at wind speeds 12 ms$^{-1}$ and 16 ms$^{-1}$. At the same wind speeds the DC-link capacitor bank lifetime of upstream turbines are 19.48 and 14.31 years and they are not equals to the lifetime of the other turbines. However, when Strategy 4 is adopted to dispatch the reactive power demand, the lifetimes are equal and slightly higher than the previous case. However, there is a small reduction in the total energy yield. Therefore, strategy 3 and 4 can be used to decide the $\alpha_i$ vector and to dispatch reactive power since the main objective is to equalise and maximise the life span of power converters. This observation is inline with the underlying idea of the control strategies formulation. Strategy 3 maximises the energy yield of the wind farm while minimising the damage of the power converters and Strategy 4 dispatches the reactive power demand while equalising the lifespan of the converters.

Performance of the formulated strategy can be compared with the method proposed in [12]. The reactive power demand
TABLE 3 Performance comparison of the reactive power dispatch strategy

| Reactive power dispatch method | Energy yield (TWh) | Lifetime (years) | Energy yield (TWh) | Lifetime (years) |
|-------------------------------|-------------------|-----------------|-------------------|-----------------|
| Strategy 3                    | 12 ms⁻¹           | 16 ms⁻¹         | 12 ms⁻¹           | 16 ms⁻¹         |
| Strategy 3                    | 0.8655            | 1.197           | 19.48             | 14.31           |
| Strategy 3                    | 0.7484            | 1.196           | 21.8              | 13.91           |
| Strategy 4                    | 16 ms⁻¹           | 12 ms⁻¹         | 16 ms⁻¹           | 12 ms⁻¹         |
| Strategy 4                    | 0.8649            | 1.193           | 19.5              | 14.4            |
| Strategy 4                    | 0.7484            | 1.196           | 21.8              | 13.91           |

Damage of the DC-link capacitor bank of power converters should be minimised to reduce CoE while maximising rate of energy extraction. To this end, wind farm control strategies should be based on lifetime and energy. Lifetime-based control strategy (strategy 4) equalise life while having higher power output at the wind speeds above the rated value. Total energy-based control strategy (strategy 3) does not equalise lifetime of DC-link capacitor banks at any wind speed, although it has a higher power output at the wind speeds below the rated value. Moreover, it has a higher total energy yield at all wind speeds. Both control strategies have similar outputs, even at the dense wind turbine spacing. Therefore, strategy 3 is ideal for optimising wind farm in energy perspective and strategy 4 in the lifetime and power. Furthermore, the multi-stage control method to dispatch reactive power demand can be formulated using the lifetime and energy-based strategy considering their advantages. The operating point of a turbine and power converter can be decided using the energy-based, and the lifetime strategies, respectively to balance the life of power converters, and to extract maximum energy. The proposed methods can be implemented in existing platforms using SCADA data due to the flexibility of selected models to formulate the control strategies.

SYMBOLS

\( C_p, C_f \)  Power coefficient and thrust coefficient

\( \gamma \)  Tip-speed-ratio

\( V_{\infty} \)  Upcoming wind speed

\( V_i \)  Wind speed at the \( i \)th turbine

\( D_i \)  Separation between two wind turbines

\( \varphi \)  Displacement angle

\( R_{ce} \)  Equivalent series resistance at a given harmonic

\( \delta \)  Surface roughness factor

\( \alpha_i \)  Axial induction factor

\( M \)  Modulation index

\( P_{ci} \)  Power converted by \( i \)th wind turbine

\( P_{ci} \)  Power converted by \( i \)th converter

\( I_p \)  RMS phase current of the power converter

\( I_C \)  RMS value of the DC-link capacitor current

\( P_{core} \)  Power dissipated in capacitor core

\( T_{core} \)  Capacitor core temperature

\( L_c \)  Capacitor lifetime under certain stress level

\( L_0 \)  Nominal lifetime of the capacitor at \( T_{\text{max}} \)

\( l_c \)  Number of cycles at a certain stress level

\( D \)  Total damage of a capacitor

\( E_{ci} \)  Total energy yield of the \( i \)th wind turbine

\( L_{wc,i} \)  Capacitor bank lifetime of the \( i \)th wind turbine

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