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An optimization framework for load and power distribution in wind farms

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ABSTRACT

The aim of this paper is to develop a controller for wind farms to optimize the load and power distribution. In this regard, the farm controller calculates the power reference signals for individual wind turbine controllers such that the sum of the power references tracks the power demanded by a system operator. Moreover, the reference signals are determined to reduce the load acting on wind turbines at low frequencies. Therefore, a trade-off is made for load and power control, which is formulated as an optimization problem. Afterwards, the optimization problem for the wind farm modeled as a bilinear control system is solved using an approximation method.

1. Introduction

The research area of wind farm control can be divided into two main categories. The first is the quality control of the generated power; the second, which is the subject of interest in this paper, is the coordinated control of the power generated by each individual turbine such that the aerodynamic interactions between the turbines are minimized (Pao and Johnson, 2009). As wind farms increase in size and number, there is an increased demand for optimized performance and longer life time for each wind turbine. To extend the lifetime of the wind turbine components, a load assessment should be included in the controller design (Hammerum et al., 2007).

There are numerous scientific studies on the modeling and control of wind farms. However, the results on the combined optimization of power and load are still lacking. An example of considering the load in the overall wind farm control has been presented in Steinbuch et al. (1988). Furthermore, an optimization method to maximize the production capacity of farms based on the limitations of the physical system, such as voltage stability and generator power, has been proposed in Zhao et al. (2006). In Hansen et al. (2006), a concept with both centralized control and control for each individual wind turbine is presented. In this approach, the controllers at the turbine level ensure that the relevant reference commands provided by the centralized controller are followed. In Soleimanzadeh and Wisniewski (2011), the optimal control problem of load and power distribution is solved, providing the pitch angle and rotor speed reference signals along with power set-points to each wind turbine controller. However, in this work, only the power set-points are obtained by the wind farm controller as reference signals for the wind turbines.

Likewise, there are many studies on load reduction in single turbines (van der Hooft et al., 2003; Lescher et al., 2007; Sutherland, 2000; Hammerum et al., 2007), but the results on load control in wind farms are still lacking.

In this regard, the aim of this study is to develop a wind farm controller for the optimal distribution of power references among wind turbines while it lessens low frequency structural loads. The controller computes the required reference signals for each individual wind turbine controller. The problem has been formulated as a linear quadratic regulator (LQR) problem with constraints on the state and input, subject to a wind farm dynamic model. The wind farm dynamic model delivers an approximation of the wind speed in the vicinity of each wind turbine (Soleimanzadeh and Wisniewski, 2010a), which is suitable for optimization.

The optimal control problem is solved using model predictive control methods, and the results have been compared to the results of a numerical optimization method that uses a nonlinear model of the wind farm.

The output of the farm controller is the vector of power reference signals for each wind turbine controller. The farm controller does not directly consider the individual wind turbine controllers. However, to provide the optimal pitch angle for the wind farm control loop, the dynamics of the wind turbines have been partly combined with the wind farm dynamic model.

This paper first gives a brief overview of the wind farm model. Subsequently, the approach for the controller design is explained,

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and the optimal control problem is formulated. Finally, the optimal control problem has been solved, and the results are compared to the numerical simulation.

2. Wind farm model

A dynamical model for the flow in wind farms has been presented in Soleimanzadeh and Wisniewski (2010a) and Soleimanzadeh and Wisniewski (2010b), which calculates an approximation of the mean wind speed over the farm, especially in the vicinity of each wind turbine. This model represents the wind farm flow model approximated by ordinary differential equations, which will be applied in the wind farm control algorithms.

The modeling commences with the flow model (Navier–Stokes equations) for the whole wind farm, assuming that there is no wind turbine effect. The wind turbine dynamics are added afterwards, and their influence on the wake is studied. In this regard, we start by finding a linear approximation to the Navier–Stokes equations in 2-D at the hub height. Afterwards, the dynamics of the wind turbines correspond to the pressure and force terms of the equations (the drop pressure at the location of a wind turbine is a function of thrust coefficient using the momentum theory (Burton et al., 2001), and the force term at the location of each turbine is the thrust force).

The next step has been to divide the whole wind farm into non-overlapping cells and then define the flow equation in each cell such that the equation agrees on the boundaries of the cells. The spatial discretization for these equations is performed using the finite difference method (FDM) and the partial differential equations (PDE) have been transformed into ordinary differential equations (ODEs). The model is considered to be in the far wake region, and the ambient shear flow has been neglected. The profile of velocity deficit is assumed to be axis-symmetric. Finally, the dynamic equations of the wind farm have been written in the following form, expressed in Soleimanzadeh and Wisniewski (2010a) and Soleimanzadeh and Wisniewski (2010b)

$$\frac{dx_1(t)}{dt} = f_1(x_1(t),\ldots,x_n(t),u_1(t),\ldots,u_m(t)), \tag{1}$$

$$\vdots$$

$$\frac{dx_n(t)}{dt} = f_n(x_1(t),\ldots,x_n(t),u_1(t),\ldots,u_m(t)). \tag{2}$$

The equations above can be summarized as follows, when the coefficients of the ODEs are re-written in the following matrix form:

$$\dot{x}(t) = Ax(t) + \tilde{B}\tilde{u}(t) + \sum_{j=1}^{n}(x(t)^T\tilde{N}_j)\tilde{u}(t). \tag{3}$$

In this equation, x is a vector in $\mathbb{R}^n$ that represents the average wind speed over each partition in a time period of 5–10 min, where n is the number of partitions covering the wind farm.

The matrix $A(t)$ is a block diagonal matrix in $\mathbb{R}^{n\times n}$; $\tilde{u}$ is the thrust coefficient in $\mathbb{R}^m$, where m is the number of wind turbines. The dimension of the matrices $\tilde{B}$ and $\tilde{N}_j$ is respectively $n\times m$ and $1\times m$.

In the following, $\tilde{u}$ (the thrust coefficient) is obtained based on $u = P_{ref}$, which is the control input of the farm controller

$$\tilde{u}_i = \frac{u_i}{0.5\rho\pi R^2(1-a_i)x_i^3} \Rightarrow \tilde{u} = K(x)u, \tag{4}$$

where $u_i = P_{ref}^{WT_i}$, ρ is the air density, R is the rotor diameter, and a_i is the induction factor of the ith turbine. Substituting $\tilde{u}_i$ in (3) with its equivalent in (4), the wind farm model is written as follows:

$$\dot{x}(t) = Ax(t) + Bu(t) + \sum_{j=1}^{n}(x(t)^T N_j)u(t), \tag{5}$$

where $A\in\mathbb{R}^{n\times n}$ and $B\in\mathbb{R}^{n\times m}$; thus, $N_j\in\mathbb{R}^{1\times m}$.

The model has been validated using real measurement data from the EWTW wind farm in the Netherlands. The measurements were the mean wind speed over a specific time interval. Therefore, the model has been simulated for this specific time interval, mean wind speed has been calculated, and the results are compared to the EWTW data. This model provides an approximation of wind speed over the entire farm and presents it as an approximate description of what is occurring downstream of a wind farm. Therefore, it is useful to estimate the loads and total power production of wind farms.

3. Control strategy

The wind farm controller design in this paper is based on the wind turbine control strategy. At low wind speeds, the rotor speed in a wind turbine changes according to the wind speed to maintain the optimal tip speed ratio while the pitch angle is kept constant. At high wind speeds, the rotor speed is kept constant, and the pitch angle is increased to limit the power captured at its rated value. The wind turbine control system receives the optimal power set-points from the wind farm controller. Additionally, the power set-points computed by the farm controller should track the total power demanded by the operator. Furthermore, it should be determined by considering load minimization.

Above the rated wind speed, the pitch angle variations strongly influence the turbine dynamics, in particular, the tower dynamics. As the blades pitch to regulate the aerodynamic torque, the aerodynamic thrust on the rotor changes substantially, which affects the structural dynamics of the wind turbine (Burton et al., 2001).

As analyzed in Suryanarayanan and Dixit (2007), the blade edge motion is strongly coupled with the tower side-to-side motion and the drive train torsion. Accordingly, one of our objectives is to reduce the blade bending (bb) moment in both the edge and flap directions and to reduce the tower bending (tb) moment in the fore-aft direction. Based on the model explained in Brand and Wagenaar (2010), both the tower and blade bending moments can be estimated as a function of the C_T coefficient.

The tower bending moment due to the thrust force, $F_T(C_T,V)$, will be assumed to be (Brand and Wagenaar, 2010)

$$M_{tb}(C_T,V) = hF_T(C_T,V), \tag{6}$$

where h is the tower height and F_T is given by

$$F_T(V,\beta,\lambda) = \tfrac{1}{2}\rho\pi R^2V^2C_T(\beta,\lambda), \tag{7}$$

where ρ, R and V are, respectively, the air density, rotor radius and wind speed. Additionally, $C_T(\beta,\lambda)$ is the thrust coefficient. Therefore, the tower bending moment is expressed as

$$M_{tb}(\beta,\Omega R/V) = k_{tb}V^2C_T(\beta,\Omega R/V), \tag{8}$$

with $k_{tb} = \frac{1}{2}h\rho\pi R^2$.

The effective blade bending moment M_{bb} due to the edge and flap motion of the blade is modeled as follows (Brand and Wagenaar, 2010):

$$M_{bb}^2 = (\tfrac{1}{9}F_b^2 + \tfrac{25}{1152}m_{bd}g^2)D^2, \tag{9}$$

where m_{bd} is the mass of the blade, g is the acceleration of gravity, D is the rotor diameter, and F_b for a 3-blade wind turbine is

$$F_b = \frac{\rho\pi D^4}{12}\frac{\Omega^2 a(1-a)}{\lambda^2}, \tag{10}$$

where a is the induction factor of a turbine. Combining (9) and (10) and substituting $\lambda = \Omega R/V$, the effective blade bending moment is

$$M_{bb}^2 = k_{11}(V^2 a(1-a))^2 + k_2 = k_1(V^2 C_T(\beta,\lambda))^2 + k_2, \tag{11}$$

where $k_1 = k_{11}/4 = (\pi\rho D^5/108R^2)^2$ and $k_2 = 25 m_{bd} g^2 D^2/1152$.

4. Optimization problem

4.1. Load control

In this section, we approximate the bending moment equations (8) and (11) with two linear functions. The linearization will be around the mean wind speed, the mean pitch angle and the mean rotor speed

$$M_{tb}(\Omega,\beta,V) \approx M_{tb}(\overline{\Omega},\overline{\beta},\overline{V}) + \left.\frac{\partial M_{tb}}{\partial \Omega}\right|_{\overline{\Omega},\overline{\beta},\overline{V}} (\Omega - \overline{\Omega}) + \left.\frac{\partial M_{tb}}{\partial \beta}\right|_{\overline{\Omega},\overline{\beta},\overline{V}} (\beta - \overline{\beta}) + \left.\frac{\partial M_{tb}}{\partial V}\right|_{\overline{\Omega},\overline{\beta},\overline{V}} (V - \overline{V}). \tag{12}$$

Therefore, M_{tb} can be approximated by the following equation:

$$M_{tb}(\Omega,\beta,V) \approx \delta_0 + \delta_1\Omega + \delta_2\beta + \delta_3 V, \tag{13}$$

where δ_i, $i=1, 2, 3$, are the linearization factors obtained from (12). In a similar way, a linear approximation for the blade bending moment is

$$M_{bb}(\Omega,\beta,V) \approx \varsigma_0 + \varsigma_1\Omega + \varsigma_2\beta + \varsigma_3 V, \tag{14}$$

where ς_i, $i=1, 2, 3$ are the linearization factors. The linear approximation above for the tower and blade bending moments are used in the wind farm cost function and should be minimized to reduce the structural loads. However, controlling the loads on the farm level will be much slower than the load control by the wind turbine controller. The wind turbine controller changes β_{ref} to control the dynamic loads, and the wind farm controller determines P_{ref} such that the static loads are minimized. Therefore, a low-pass and a band-pass filter are used to drop the high frequency tower and blade bending moments.

The tower bending moment is limited by a simple recursive low-pass filter with a corner frequency of 0.3 Hz. The band-pass filter for the blade bending moment has a center frequency of 0.6 Hz and a bandwidth of 0.35–0.85 Hz (based on NREL 5 MW wind turbine data, Jonkman et al., 2009).

4.2. Power reference determination

On the other hand, the system operator determines the power demanded from the wind farm. Therefore, the power captured from the wind farm, which is the sum of the output powers from all wind turbines, should track the power demanded. Thus. $\sum_i^N P_{Wt_i}(V_i,C_{p_i}) - P_{ref}^{Wf}$ should be minimized. In other words, the power produced by all turbines $\sum_i^N P_{Wt_i}(V_i,C_{p_i})$ should follow the wind farm power reference signal, which is determined by the system operator. This corresponds to the fact that the power produced by each turbine, $P_{Wt_i}(V_i,C_{p_i})$, should follow each reference signal $P_{ref}^{Wt_i}$. This reference signal for each wind turbine has to be determined by the wind farm controller.

When the wind speed is above the rated power, the rotor speed is kept constant, and the power coefficient, $C_p(V_i,\beta_i)$, depends on the pitch and wind speed. Therefore, the power produced is written as a function of the pitch angle $P_{Wt_i}(V_i,\beta_i)$. In summary, the following value is a part of a cost function:

$$P_{Wt_i}(V_i,\beta_i) - P_{ref}^{Wt_i}, \tag{15}$$

where P_{ref}^{Wt} should be obtained during the minimization process.

Therefore, the following terms should be minimized with the first term due to the power reference determination and the second term $M_{tb} + M_{bb}$:

$$Z_i = \left|(P_{Wt_i}(V_i,C_{p_i}) - P_{ref}^{Wt_i})\right| + c_1((\varsigma_1+\delta_1)\Omega + (\varsigma_2+\delta_2)\beta + (\varsigma_3+\delta_3)V), \tag{16}$$

where $\sum_i^N P_{ref}^{Wt_i} = P_{ref}^{Wf}$ and c_1 is a weighting factor. At high wind speed, the controller keeps the rotor speed constant, and thus we can neglect the term $(\varsigma_1+\delta_1)\Omega$. Moreover, replacing P_{Wt_i} with its linear approximation, which, at high wind speeds (after neglecting the constants) is $k_{p_1}V + k_{p_3}\beta$, the function to be minimized is

$$Z_i = \left|k_{p_1}V + k_{p_3}\beta - P_{ref}^{Wt_i}\right| + c_1((\varsigma_3+\delta_3)V + (\varsigma_2+\delta_2)\beta). \tag{17}$$

Furthermore, defining $u = P_{ref}^{wt}$ and x to be the wind speed (the same as (5)), we may re-write (17) in the following form:

$$Z = Gx + Hu + f(\beta), \tag{18}$$

where the affine term $f(\beta)$ is the function of β expressed in (17), where β is calculated by the wind turbine controllers.

In this paper, reducing the load and power production are equally important. Therefore, in the simulations, c_1 is set equal to one.

4.3. Optimal control

The block diagram of the optimal control problem is shown in Fig. 1. The load control focuses on minimizing the loads at low frequencies; in other words, the static loading of the turbines is controlled by the wind farm controller. The individual wind turbine controller is responsible for dynamic load control. The dynamic of the system is (5). In Fig. 1, the WT block represents the relation between P_{ref}, the input to the wind turbine controller, and β_{ref}. The details are shown in Fig. 2 (Jonkman et al., 2009), which is a PI controller and is a part of the control system of the wind turbine. The PI controller is responsible for pitch control and for producing the pitch reference signal. The pitch reference signal is the feedback to the wind farm controller.

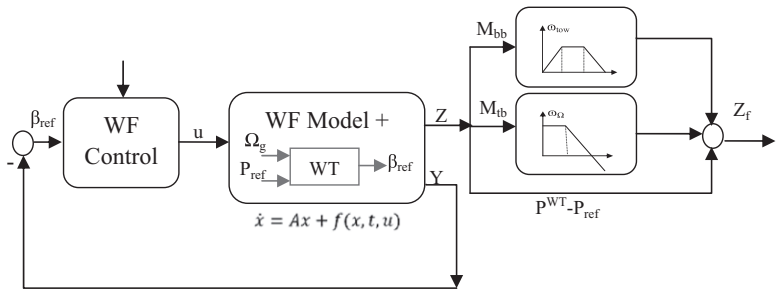

Fig. 1. The wind farm control block diagram.

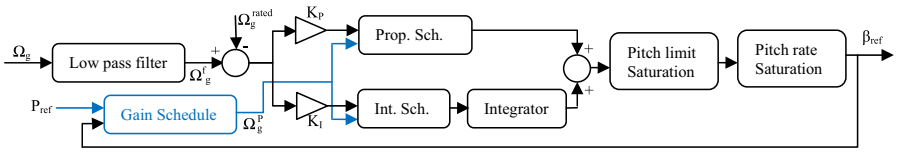

Fig. 2. WT block; the pitch control system of a wind turbine (Jonkman et al., 2009).

In Fig. 1, $Y=\beta$. To find an expression for the output Y based on the state x and input u, we may approximate this relation in the following way. The C_T coefficient of each wind turbine has been approximated by a polynomial using the lookup table of the NREL 5MW (Jonkman et al., 2009) wind turbine, and the polynomial is approximated by a linear function:

$$C_T(\beta,\lambda)=\sum_{i=0}^{3}\sum_{j=0}^{3}k_{i,j}\beta^i\lambda^j\approx\iota_0+\iota_1\lambda+\iota_2\beta, \tag{19}$$

where ι_i are the linearization factors. Here

$$C_T(\beta,\lambda)=\iota_0+\iota_1\lambda+\iota_2\beta,$$

$$C_T(P_{ref}^{WT},x)=\frac{P_{ref}^{WT}}{K_p x^3(1-a)}, \tag{20}$$

where Ω is assumed to be constant, $K_p=\frac{1}{2}\rho\pi R^2$ and a is the induction factor that is entered into the equations using (20). Setting the equations above equal to each other and re-arranging, we will have

$$\beta_{ref}^{WT}(P_{ref}^{WT},x)=\frac{P_{ref}^{WT}}{\iota_2 K_p x^3(1-a)}-\frac{1}{\iota_2}(\iota_0+\iota_1\lambda)\approx k_{\beta_0}+k_{\beta_1}x+k_{\beta_2}u, \tag{21}$$

where, neglecting the constant term, $Y=\beta=Cx+Du$, with $C=k_{\beta_1}$ and $D=k_{\beta_2}$.

When the wind speed is below the rated speed, we define $Y=\Omega$ and in a similar way, it can be approximated as $Y=\Omega=\grave{C}x+\grave{D}u$, where $\grave{C}$ and $\grave{D}$ are the linearization factors.

The cost function is defined as

$$J(P_{ref}^{Wt_i})=\int_{t_0}^{t_f}\sum_{i}^{N}[Z_i^T Z_i]\,dt=\int_{t_0}^{t_f}[x^T Fu+u^T Ru+x^T Qx]\,dt, \tag{22}$$

where $Q=G^T G$, $R=H^T H$ and $F=G^T H$. Moreover

$$\sum P_{ref}^{Wt}=P_{ref}^{Wf},$$

$$x(t_0)=x_0,\quad x(t_f)\text{ is free},\quad t=[t_0,t_f]$$

$$u\in[u_{min},u_{max}],$$

$$x\in[x_{min},x_{max}] \tag{23}$$

subject to the differential equation (5).

After linearizing the bilinear differential equation around the operating point, as $\dot{x}=Ax+Bu$, the optimal control problem is a constraint quadratic problem subject to a linear system, where the constraints are imposed on both the state and input. This problem can be solved using a standard model predictive control (MPC) approach.

However, linearizing the load, power and dynamic model of the system to obtain the quadratic structure will reduce the accuracy of the results and the load control. Therefore, the problem has also been formulated in another way, with less linearization and a better approximation of the load and power set points.

In the alternate formulation of the control problem, the cost function contains the tower and blade bending moments for low frequencies, and Eq. (15), without linearization, to determine the power set point. Moreover, the wind speed all over the wind farm is obtained off-line from the dynamic model of the flow in the farm, which is a bilinear system, and then it is implemented in the optimal control problem. This process will lead to a nonlinear optimization that is solved numerically using the Yalmip (Löfberg, 2004) toolbox in MATLAB.

5. Results and discussion

The optimal control problem (22) and (23) has been solved using the Model Predictive Control toolbox in MATLAB for a small wind farm with five wind turbines in a row, where the distance between two wind turbines is almost four rotor diameters. The reason is explained in Fig. 3(a) and (b), which show a wind farm with 25 wind turbines, where the direction of the wake propagations are depicted with thick solid lines. As it has been shown, the maximum wake interaction for a row of wind turbines occurs when the wind direction is parallel to the row. Therefore, the optimal control problem is solved for a sample farm with five wind turbines in a row, and the wind direction is assumed to be parallel to the row of turbines.

The control input u, which is the vector of the power references, has been obtained as a time series. Then, the average value of the power reference in 10 min for each wind turbine is calculated.

The results have been illustrated in Fig. 4 for a wind speed below the rated wind speed in the blue graph. In this case, the wind speed at the vicinity of each wind turbine is below the rated speed (the free stream wind speed is approximately 8 m/s), and the total power demanded from the wind farm is 4.9 MW. In addition, the optimal control problem excluding the linear approximations has been solved numerically using the Yalmip toolbox (Löfberg, 2004) in MATLAB. The results, the average power set-point for each wind turbine, are depicted in Fig. 4 in the red graph. The outcome of the controls mentioned above for the wind farm has been compared to that of a conventional wind farm control, where the power set-points are divided between the turbines proportional into the power coefficients. In the conventional method, the controller either extracts the maximum available power or dispatches the set-points equally between the turbines based on the amount of power demanded and the operating regime of the wind turbines. The numerical results are expected to be closer to reality, because linear approximations are used less often in this approach.

Based on these results, if we extract less power from the first wind turbine of the row, we will be able to extract more power from downstream turbines, such that the total produced power is equal to the power demanded and the structural loads on the turbines will be reduced. A comparison between the tower bending moments in all three cases is illustrated in Fig. 5. Due to the scale of the graphs, the plots seem to be the same, but there are differences between them. The differences between the case without a controller with the other two cases are also depicted in the figure.

The calculations have been repeated for a case when the free space wind speed is above the rated speed, and the results are depicted in Fig. 6.

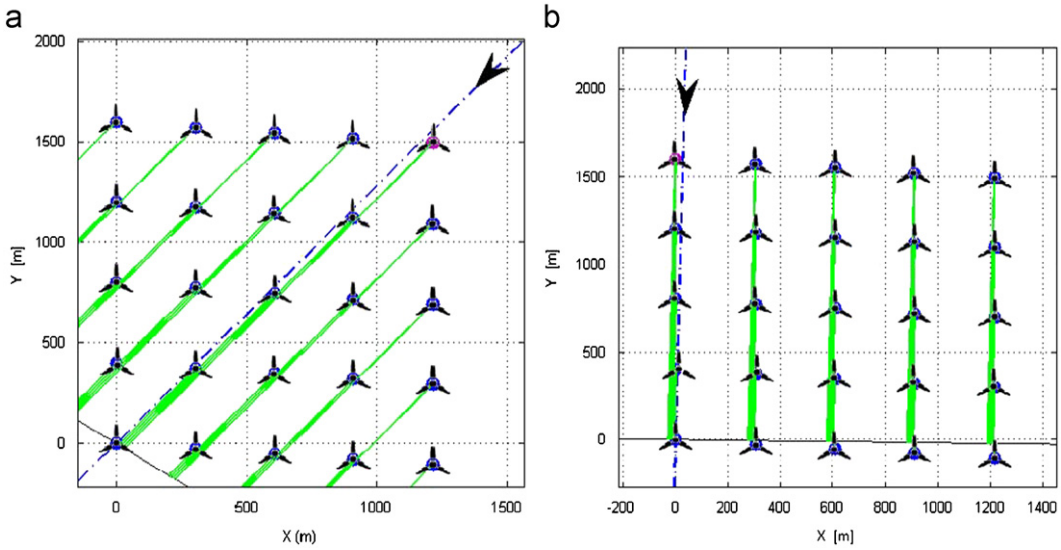

Fig. 3. Two wind directions that produce the maximum wake interaction; the reason for choosing one row of turbines for simulation: (a) wind direction 36° and (b) wind direction 1°.

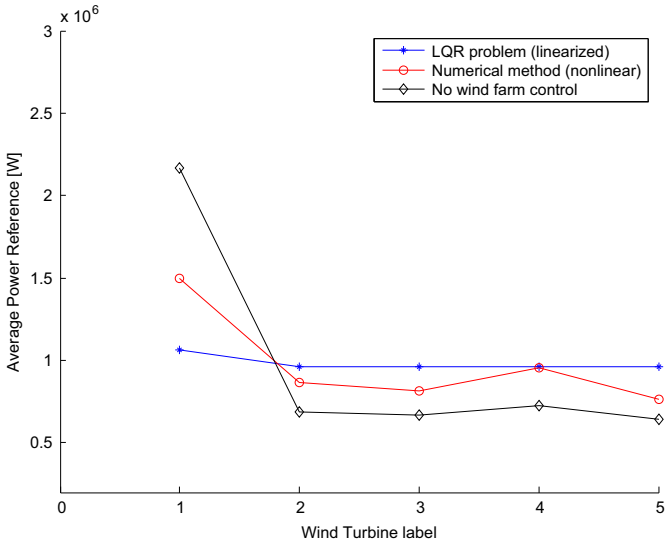

Fig. 4. Power references for each wind turbine in a row (five turbines) below the rated wind speed.

It should be noted that whenever the free space wind speed is a slightly higher than wind turbine rated speed, with very low turbulence intensity, it may cause the velocity deficit to the below rated speed in the vicinity of some of the down wind turbines.

Here, the free space wind speed is approximately 14 m/s, and based on the wind farm dynamical model for five wind turbines in a row with maximum wake interactions, the wind speed that reaches the last turbine of the row is below the rated speed. Fig. 6 shows the optimal way to distribute the power references between the wind turbines with regard to load reduction.

The first four wind turbines are able to produce nominal power, and the total power demanded from the farm is 18.9 MW. The results show that if less power is extracted from the upstream wind turbines, it will influence the wake effect on the last turbine of the row, such that the turbine will be able to produce more power. Thus, the total power demanded will be satisfied, and the low frequency loads on the first four wind turbine have decreased. The last wind turbine will experience an increased static load; however, the structural loads due to the turbulent wake of the upwind turbines are reduced on this turbine.

In the case where all the turbines are operating above the rated wind speed and are able to produce nominal power, the power references will be divided between the turbines proportionally.

The load reduction in the farm is found by comparing the blade and tower bending moments with and without the controller. Although the power references are the same for the first four wind turbines, the turbines experience different bending moments due to the different wind speeds and turbulence intensity conditions. Because, the loads are considered for low and medium frequencies, the static loads are minimized. Therefore, we do not expect a great improvement in the overall loads. Specifically, the average tower bending moments for each wind turbine with a free stream wind speed of 14 m/s are depicted in Fig. 7. As expected, the static load on the first four turbines has been decreased; for example, using the numerical method, the loads on the first wind turbine decreased by 1.5% and, on the next three turbines, by 4%. However, in this approach, the static load on the last turbine has increased by 15% because the power production level is higher. Nevertheless, because this turbine is able to produce more power than before (compared to the case with no farm controller, a higher wind speed is available at this turbine), the effect of the upwind turbine wakes has been reduced on this turbine. In other words, we conclude that the dynamic loads, which are the origin of fatigue, are decreased on this turbine, which is a hypothesis that needs to be proven in future works.

6. Conclusion

In this work, a centralized optimal controller has been developed for wind farms. The main advantage of this controller is that it considers power optimization and load minimization simultaneously. The controller calculates and sends the power reference signals to each wind turbine of the farm, such that the structural loads on the turbines are reduced. The loads that are considered for minimization are the tower and blade bending moments at low frequency. The wind farm control strategy developed in this work can easily be implemented on large wind farms with

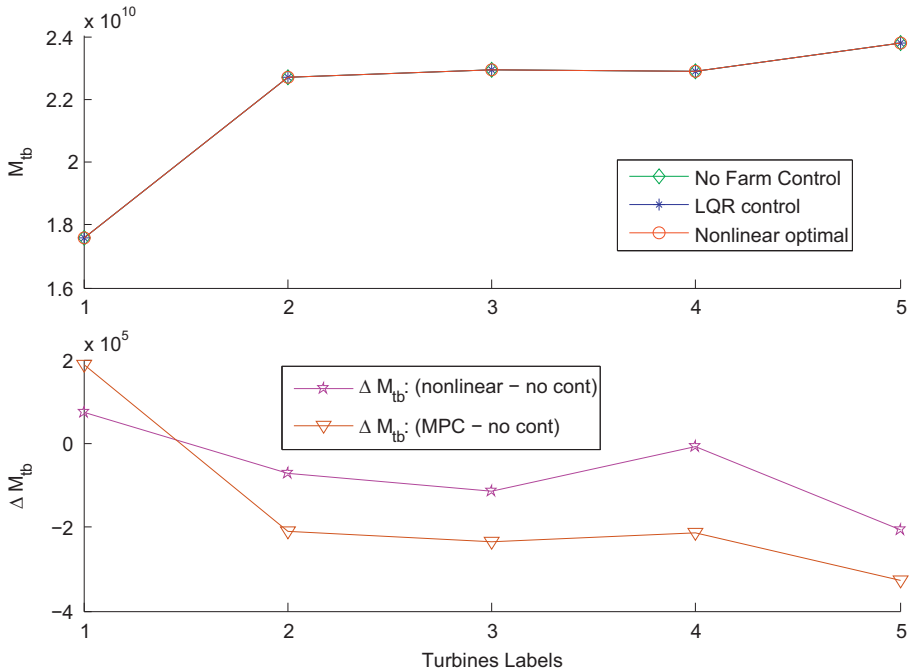

Fig. 5. Changes in mean tower bending moments after using the controller for the five turbines in a row.

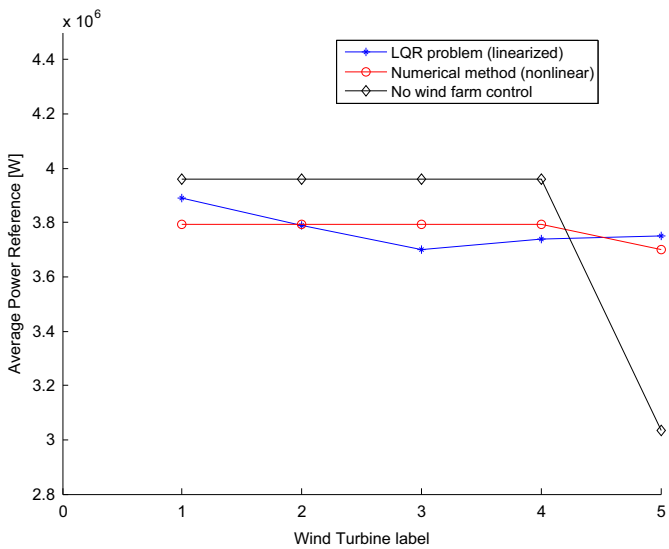

Fig. 6. Power references for each wind turbine in a row (five turbines) above the rated wind speed.

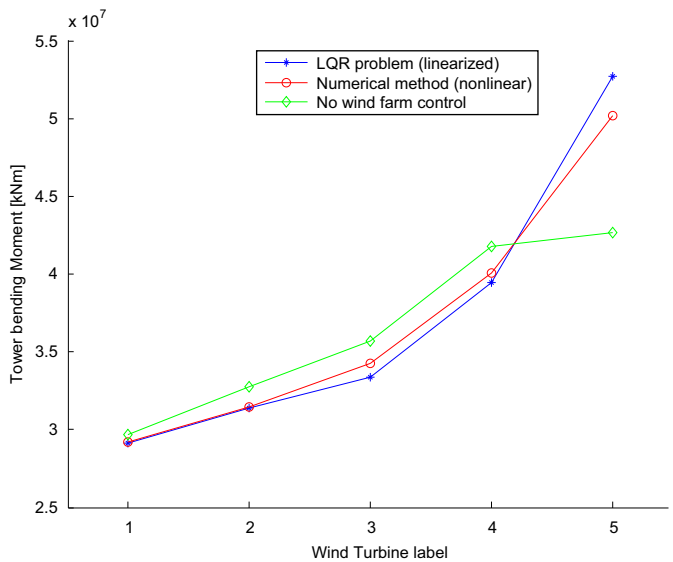

Fig. 7. Reduction in the mean tower bending moments after using the controller for the five turbines in a row; the free stream wind speed is 14 m/s.

variable wind speeds and arbitrary wind directions. The only requirement is that the wind farm model should be extended using meandering effects and turbulence models. To provide the optimal pitch angle for the wind farm controller, the dynamics of wind turbines have been partly combined with the wind farm dynamic. We remark that the farm controller does not deal with the wind turbines individual controllers.

Since mostly dynamic loads are responsible for fatigue and the reduced life time of wind turbines in wind farms, the main limitation of this work is considering the static loads of the turbines. The reason is that the individual wind turbine controllers control the dynamic load; moreover, considering dynamic loads at the farm scale requires very fast computation facilities.

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