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Support for Primary Frequency Control by a Wind Farm Using Wake Propagation Delay

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Abstract: A wind farm can be operated in the Maximum Power Point Tracking (MPPT) mode where the generation of each turbine is individually maximized. In contrast, a wind farm can be operated in the Collaborative Power Maximization (CPM) mode where the generation is maximized on a wind farm level considering wake effect. Normally, the CPM mode is obviously better than the MPPT mode in terms of the amount of generation. In this study, it is suggested that a wind farm in the CPM mode can support primary frequency control by temporarily changing into the MPPT mode. However, subsequent frequency drop is inevitable when the wind farm is returning to the CPM mode. In order to address this problem of the frequency drop, it is demonstrated that the duration between mode changes should be set sufficiently large considering wake propagation delay. For further mitigation of the frequency drop, a ramping restoration method of axial induction factors is proposed. The effectiveness of the proposed approach is verified by the simulations with a wind farm with ten turbines in a row.

Key words: Iterative optimization, power maximization, wake effect, wind farm control, CPM

INTRODUCTION

Wind energy has recently been considered as one of major renewable energy sources to address the environmental issue on electricity generation. Therefore, globally cumulative installed capacity of wind power has exponentially increased during the last 10 years from 73,957 MW in 2006 -432,883 MW in 2015. European Union (EU) also sets an aggressive goal of increasing the penetration level of wind power from 14% in 2020 up to 28% in 2030. It is expected that the integration of wind power will continue to increase in many countries according to government directives. In practice, wind farms are preferred to individual turbines because economies of scale can reduce the installation cost (Semsri *et al*., 2016; Alam *et al*., 2016; Marat *et al*., 2016) and aggregation can help reducing variability and improving predictability of wind power (Holttinen *et al*., 2009). Accordingly, the number and size of wind farm also are expected to become larger (Spudic *et al*., 2011). The preference for, a wind farm with large capacity is possibly operated in a similar way as a conventional power plant (Chien and Yin, 2009; Yerzhan and Koshumbaev, 2016). Thus, it is required for wind farms to provide frequency control capabilities similar to those of conventional generators. Meanwhile, a wind farm can be operated in the Maximum Power Point Tracking (MPPT) mode where the generation of each turbine is individually maximized. In contrast, a wind farm can be operated in the Collaborative Power Maximization (CPM) mode where the generation is maximized on a wind farm level considering wake effect. From the perspective of the wind farm, the amount of power generation in the CPM mode is obviously larger than that in the MPPT mode. Therefore in normal situations, it is desirable to operate a wind farm in the CPM mode.

This study focuses on Primary Frequency Control (PFC) among the control capabilities, particularly in an under-frequency situation. A straightforward method for supporting PFC by a wind farm involves preparing a generation margin or reserve by generating less than the possible maximum power (Marden *et al*., 2013). The critical drawback of this method is that wind power generation is reduced even during normal operation. Consequently, benefits from wind power such as low CO_2 emission and low variable cost are weakened. In another approach called inertial control a wind farm can generate the maximum power during normal operation and an additional power for PFC is obtained from the kinetic energy stored in the rotor of wind turbines (Ekanayake and Jenkins, 2004). In this study, it is suggested that a wind farm in the CPM mode can support PFC by temporarily changing into the MPPT mode. However, when the wind farm is returning to the CPM mode, subsequent frequency drop is inevitable because of dynamic properties of wake in a

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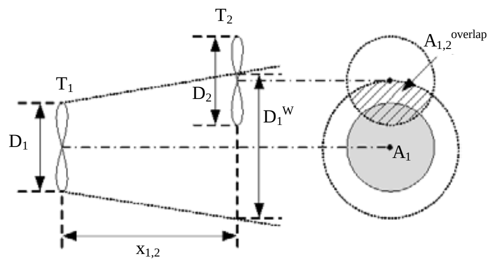

Fig. 1: Two-turbine configuration and the associated parameters for describing the wake interaction model

wind farm. In order to address this problem of the frequency drop, it is demonstrated in this study that the duration between mode changes should be set sufficiently large considering wake propagation delay. For further mitigation of the frequency drop, a ramping restoration method of axial induction factors is proposed.

Wake interaction model: The core of the wake model is to calculate the velocity deficit of the wake. When the velocity deficit δV_i of the turbine T_i is determined, the wind velocity V_i is represented as:

$$V_i = V_\infty(1-\delta V_i) \quad (1)$$

where, V_∞ is the incident wind speed. Let us consider the two-turbine configuration as shown in Fig. 1. The velocity deficit of the upwind turbine T_1 or δV_i is obviously equal to zero and $V_1 = V_\infty$. When the thrust coefficient of the turbine T_i is set to $C_{t,1}$, the velocity deficit of the downwind turbine T_2 becomes:

$$\delta V_2 = V_\infty\left(1-\sqrt{1-C_{t,1}}\right)\left(\frac{D_1}{D_1+2kx_{1,2}}\right)^2\frac{A_{1,2}^{overlap}}{A_1} \quad (2)$$

Where:

D_1 = The diameter of the turbine T_1
k = Wake decay coefficient
$x_{1,2}$ = Distance between the turbines T_1 and T_2
A_i = The area of the circle with the diameter
D_i, $A_{1,2}^{overlap}$ = The overlapped area between the circles with the diameters D^W_1 and D_2

The wake diameter can be computed as:

$$D_1^W = D_1 + 2kx_{1,2} \quad (3)$$

The axial induction factor α_i which is defined as an initial velocity deficit between the free stream and the rotor plane can be expressed with the thrust coefficient $C_{t,i}$ as:

$$a_i = \frac{1-\sqrt{1-C_{t,i}}}{2} \quad (4)$$

By substituting Eq. 4 into Eq. 2, δV_2 can be represented as:

$$\delta V_2 = V_\infty \cdot 2a_1\left(\frac{D_1}{D_1+2kx_{1,2}}\right)^2\frac{A_{1,2}^{overlap}}{A_1} \quad (5)$$

This two-turbine configuration can be generalized to be the case when the velocity deficit is induced by multiple turbines. Let us assume the subscript i of T_i is sorted in order such that smaller values mean upwind positions. Then, the wind velocity V_i of the turbine T_i is determined as by Katic *et al*. (1986) and Marden *et al*. (2013):

$$V_i = V_\infty\left(1-\sqrt{\sum_{m=1}^{i-1}\left(a_m c_{m,i}\right)^2}\right) \quad (6)$$

where, α_i is the axial induction factor of the turbine T_i and:

$$c_{m,i} = \left(\frac{D_m}{D_m+2kx_{m,i}}\right)^2\frac{A_{m,i}^{overlap}}{A_m} \quad (7)$$

where, D_m, x_m, A_m and $A_{m,i}^{overlap}$ are the diameter, distance, area of circle and overlapped area between circles for the corresponding turbines, respectively. Once the wind velocity V_i is determined, the power P_I generated by the turbine T_i is determined as:

$$P_i = \frac{1}{2}\rho A_i C_{p,i} V_i^3 \quad (8)$$

Where:

ρ = The density of air
$C_{p,i}$ = The power coefficient of the turbine T_i

which is a function of as α_i:

$$C_{p,i} = 4a_i\left(1-a_i\right)^2 \quad (9)$$

MATERIALS AND METHODS

Method for primary frequency control: Without the wake effect, the Maximum Power Point Tracking (MPPT) operation of individual wind turbines results in the maximum generation of a wind farm. With the wake effect, however, the generation of a wind farm can be maximized when some upwind turbines generate less than the available power from the MPPT operation. This implies that upwind turbines have reserve power at the turbine level but there is no reserve power at the wind farm level. It should be pointed out that such statement is only applicable in the steady state. In other words, the generation of a wind farm can be temporarily increased beyond the maximum value due to wake propagation delay (EWEA, 2008).

The wake propagation delay approaches dozens or hundreds of seconds in a normal layout of a wind farm which is consistent with the time frame of PFC. Then, if a wind farm detects a significant frequency drop or receives a request for PFC from the system operator, the wind farm has only to change the operation mode from the power maximization at the wind farm level to the MPPT at the individual turbine level. After supporting PFC, the wind farm should be restored to the power maximization mode. Considering wind farm operation can be characterized by the axial induction factors of wind turbines in a wake model, this approach for supporting PFC support with the wake propagation delay as shown in Fig. 2 where $\{\alpha^*_1, ..., \alpha^*_N\}$ and $\{\alpha^{MPPT}_1, ..., \alpha^{MPPT}_N\}$ are axial induction factors of the maximization and MPPT modes, respectively; N is the number of turbines in the wind farm; and T_{PFC} is the duration of the MPPT mode for PFC. $\{\alpha^{MPPT}_1, ..., \alpha^{MPPT}_N\}$ are always equal to {1/3, ..., 1/3} regardless of the layout of a wind farm. In contrast, $\{\alpha^*_1, ..., \alpha^*_N\}$ are determined by solving an optimization problem for the given layout of a wind farm (GWEC, 2015).

The problem of the proposed approach is that the change in operation mode causes subsequent frequency drop. The first change from the maximization mode to the MPPT mode decreases the generated power and thus, causes a frequency drop after the transient time. In the second restoration from the MPPT mode to the maximization mode, a frequency drop occurs because some upwind turbines generate less power by reducing their axial induction factors to maximize generation at the farm level. The frequency drop resulting from the proposed approach cannot be completely avoided but it can be mitigated by using an appropriate strategy on when and how operation mode changes should be made.

To mitigate the frequency drop from the first mode change, this study proposes that T_{PFC} should be sufficiently large considering the wake propagation delay. Otherwise, frequency drop becomes large because the decrease in generation from the second mode change is superposed on the decrease from the first mode change. In addition, the capability of the wind farm to support PFC is not fully utilized. For the frequency drop from the second mode change, this study proposes a ramping restoration to the maximization mode during a certain

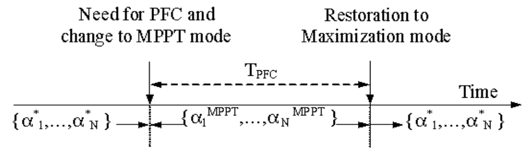

Fig. 2: Timing description of the proposed approach with the corresponding axial induction factors

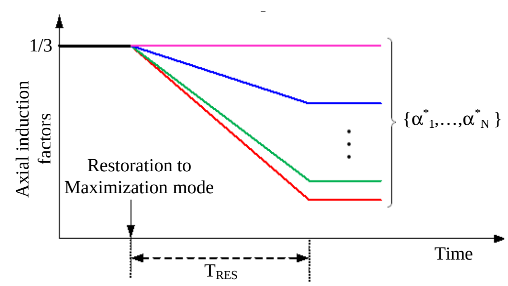

Fig. 3: Ramping restoration of axial induction factors to the power maximization mode

Time period (T_{RES}) instead of an instantaneous change as shown in Fig. 2. This ramping restoration is shown in Fig. 3. It should be noted from Fig. 3 that at least one turbine, that is, the most downwind turbine, has an axial induction factor of 1/3 even in the maximization mode. The proposed ramping method makes the decrease in generation which is caused by the reduced axial induction factors of upwind turbines, distributed in time. As a result, the steep frequency dip can be alleviated. Nonetheless, a large value for T_{RES} involves a long restoration time to the power maximization mode. Therefore, T_{RES} needs to be determined by considering the trade-off between the mitigation of the frequency drop and the fast restoration time to the power maximization mode.

RESULTS AND DISCUSSION

The effectiveness of the proposed approach is verified by the simulations with a wind farm consisting of ten turbines in a row as shown in Fig. 4. The diameter, rated wind speed and rated power are set to 80 m, $V_{rate} = 12$ m sec^{-1} and $P_{rate} = 2$ MW, respectively. Incoming wind speed is assumed as 12 m sec^{1} with the direction indicated by the arrow in Fig. 4. The density of air and the wake decay coefficient are set to $\rho = 1.225$ kg/m^3 and k = 0.04, respectively. The wind speeds of turbines are computed by the Jensen wake model (Katic *et al*., 1986) and the wake propagation delays are calculated using the method presented by Longatt *et al*. (2012). The feedback loop for PFC with other conventional generators

Table 1: Configuration of five simulation cases

Cases	Support of wind farm	T_{PFC} (sec)	Ramping restoration	T_{RES} (sec)
1	No	-	-	-
2		30	No	-
3	Yes	60		-
4		60	Yes	30
5		60		60

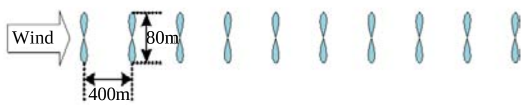

Fig. 4: Layout of the wind farm in the simulations

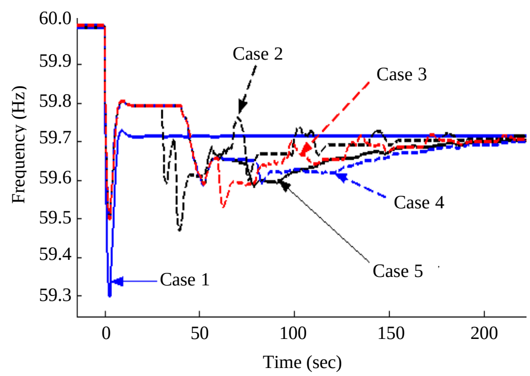

Fig. 5: Simulation result: frequency variation

and the associated parameters are taken from (Kundur, 1994). The situation giving rise to the need for PFC results from the sudden increase in load at t = 0 by 10 MW (0.1 p.u.). Five simulation cases are composed and listed in Table 1.

The simulation results are shown in Fig. 5. In all cases with the support of a wind farm, the initial frequency drop is reduced from 0.70-0.50 Hz. The first subsequent frequency drop is reduced for the large T_{PFC} (T_{PFC} = 60 sec) compared with the smaller value (T_{PFC} = 30 sec). The second subsequent frequency drop is further alleviated by the ramping restoration. Despite the longest restoration time to the power maximization mode in case V, the mitigation of the frequency drop is not significant. Thus, we conclude that case 4 is the best choice for supporting PFC by the wind farm in this study.

CONCLUSION

Widespread integration of wind farms request that they should support the grid function of primary frequency control. One of the critical disadvantages of this PFC support is that a wind farm cannot increase generation unless the amount of wind power generation is intentionally decreased in a normal operation. Therefore, this study proposed a method for a wind farm generating its maximum to support the PFC function using the dynamic property of wake propagation delay. Further, a ramping restoration method of axial induction factors was proposed to mitigate the subsequent frequency drop after the PFC support. The simulation results showed that the PFC support can be implemented with the wake propagation delay. In addition, it was examined that a deliberate strategy for recovering to the maximum generation mode should be necessary and the proposed ramping restoration method can be an effective alternative. It will be further necessary to study the performance of the proposed scheme is tested in a real wind farm, where the wake propagation delay appears with more complex properties.

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