Off-shore Wind Power Plant Shutdown Algorithm to Meet the Ramp Rate Requirement of a Grid Code in Storm-driven Conditions

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***Abstract*—In storm-driven conditions, a wind power plant (WPP) needs to be shut down to prevent damaging the wind generators (WGs). To avoid affecting grid operation this has to consider the WPP ramp-down rate requirement defined in the grid codes. This paper proposes an off-shore WPP shutdown algorithm that determines the number of WGs to shut down simultaneously to achieve this requirement. Based on the wind direction and speed measured at a wind mast (WM) installed several kilometers away from the WPP, the wind-arrival times from the wind front to each WG are calculated. Then, a sequence of WGs is generated in the order of wind-arrival times, and subsequently a group sequence is generated. The start- and end-time of each group are determined by considering the wind-arrival time and the shutdown duration. In this paper, the minimum shutdown duration without using a brake is employed to maximize the energy production. The performance of the algorithm is verified under various storm conditions. The results demonstrate that the algorithm can shut down the WPP without exceeding the required ramp-down rates and maximize the energy production during the shutdown.**

***Index Terms*—Shutdown, Grid Code, Wind Power Plant, wind mast, and Ramp rate.**

NOMENCLATURE

N_{WG}	Number of WGs to shut down simultaneously
R_{GC}	Required ramp rate in a Grid Code
R_{WG}	Ramp rate of a WG without using a brake
$T_{i,j}$	Wind-arrival times from the WM to each WG
$s_{i,j}$	Distance from the wind front to each WG
t_{down}	Duration time of the WG shutdown
$T_{GN,\ start/end}$	Shutdown start-/end-time of each group

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (2012-0009146).

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I. INTRODUCTION

A general characteristic of wind generators (WGs) is that their output power depends on the wind speed, commonly specified by what is denoted a power curve. The power curve of a WG describes the steady-state relationship between wind speed at the WG hub-height and its output power [1, 2]. The WG starts producing at cut-in wind speeds, typically around 4−5 m/s, and then the power increases with about the cube of the wind speed until rated power is reached at the rated wind speed, typically around 12−15 m/s. Above the rated wind speed, the output power is limited either by passive aerodynamic stall or by actively controlling the pitch angle of the blades.

Above the cut-out wind speed, commonly 25 m/s, the WG is stopped. This is because the mechanical stress on the structure rapidly increases with the wind speed, and as such high wind speeds generally seldom occur, the loss in annual generation due to such stopping is anyhow modest [3]. The shutdown of the WG generally starts by using a brake when the speed measured by the anemometer on the nacelle of the WG exceeds the cut-out wind speed. However, the usage of braking systems causes a predominantly high fire risk [4]. Hot fragments of the disc brake material can be broken off because of overheating during the shutdown of the WG. As a result, hydraulic hoses might be ruptured; thus, highly combustible hydraulic fluid can be expelled due to the pressure and come into touch with the hot disk brake fragments. This causes the fluid to explode into flames.

On the other hand, shutting down a large-scale wind power plant (WPP) may jeopardize grid operation [5]. Unless the grid has enough ramp-up capability to compensate the unexpected deficit of power due to the shutdown of the WPP, the grid frequency reduction and subsequent load shedding to keep the balance between generation and demand are inevitable [6−8]. To prevent this situation, countries with large wind penetration, such as Denmark, Germany, UK, and Ireland, among others, include the WPP ramp-rate requirement in their Grid Codes for connection of a large WPP [9, 10]. The ramp-rate requirement in these countries specifies 10% of the rated power per minute. Difficulty arises in meeting the ramp-rate requirement in the case of shutdown of the WPP in storm-driven conditions because it causes significant output power reduction for a very short period of time.

A shutdown algorithm of a large WPP prior to reaching a storm, without using the brake mechanism, is proposed in [11, 12]. It assumed that wind masts (WMs) are installed several kilometers away from the WPP to collect the wind speed and direction. Based on the wind information measured at the WMs, the wind-arrival times from the wind front to each WG were calculated. Among them, the minimum wind-arrival time was determined as the shutdown duration of a WG. The shutdown end-time of each WG was determined as the wind-arrival time of each WG, whilst the shutdown start-time of each WG was determined by subtracting the duration of the WG shutdown from the shutdown end-time of each WG. The shutdown algorithm can stop the WGs without using a brake and reduce partly the negative impact on the grid. However, the number of WGs that shutdown simultaneously was not considered. Therefore, this might cause the maximum ramp-down rate of the WPP to exceed the required ramp-down rate of a Grid Code, which in turn has an adverse impact on grid operation. Moreover, the shutdown starts relatively in advance because the shutdown duration of a WG was determined as the minimum wind-arrival time instead of the minimum shutdown duration of a WG. Thus, less energy production during the shutdown is inevitable.

This paper proposes an off-shore WPP shutdown algorithm to meet the ramp-down rate as specified in Grid Codes, in a storm-driven situation without using a brake. The proposed algorithm determines the number of WGs that need to shut down simultaneously. Based on the wind direction and speed measured at a WM, wind-arrival times from the wind front detected at a WM to each WG are calculated. Then, a sequence of WGs is generated in the order of wind-arrival times and subsequently a group sequence is generated. Each group consists of a predetermined number of WGs, which are shut down simultaneously. The shutdown end-time of each group is determined as the minimum wind-arrival time in the group, whilst the shutdown start-time of each group is determined by subtracting the duration of the WG shutdown from the shutdown end-time of each group. In this paper, to maximize the energy production during the shutdown, the duration time of the shutdown is determined as the smallest one, for which the WG can be shut down without using a brake. If the shutdown start- and end-time of adjacent groups overlap, the start- and end-time of the preceding group are re-scheduled by considering the overlap time. The performance of the proposed algorithm is verified under various storm conditions varying the speed and direction of the wind.

II. Off-shore Wind Power Plant Shutdown Algorithm

In a storm-driven situation, all WGs in a WPP should be shut down to protect them. While shutting them down, it is desirable to meet the ramp-rate requirements in a grid code and maximize the energy production. This paper proposes a WPP shutdown algorithm that not only meets these requirements but maximizes the energy production too. In this paper the number of WGs to be shut down simultaneously is determined to meet the requirement, and the minimum shutdown duration without using a brake is used to maximize the energy production.

The proposed algorithm uses the information of the wind speed and direction to calculate the wind-arrival time from the wind front to each WG as in [11, 12]. It assumes that WMs are installed several kilometers away from the WPP to collect the wind information as shown in Fig. 1. Four WMs are positioned at the edges of the outer square, where the direct distance from the inner square to the outer square is denoted as d_m. d_m is determined by considering the highest wind speed in the installed area. However, determination of d_m is beyond the scope of this paper. The distance between two adjacent WGs is denoted as d. v and α represent the wind speed and direction measured at a WM, respectively. For convenience, the proposed shutdown algorithm assumes that off-shore has an apparent wind front and no creation of swirls from the WM and the WPP in a storm-driven situation.

A. Determination of the number of the WGs to be shut down simultaneously

The proposed algorithm splits the WGs into the groups that are shut down sequentially. The WGs in each group are shut down simultaneously. The number of WGs (N_{WG}) in each group is determined in advance in order to meet the required ramp-down rate (R_{GC}) in a Grid Code by considering the ramp-down rate (R_{WG}) of a WG without using a brake. As a smaller ramp-rate of the group requires an early shutdown it would be ideal to match R_{GC} and the ramp-rate of each group, i.e.,

$$R_{GC} = N_{WG} \times R_{WG} \tag{1}$$

In addition, R_{WG} has the maximum rate at which a WG can be shut down without using a brake. Thus, N_{WG} should meet the following equation:

$$\frac{R_{GC}}{\max R_{WG}} \le N_{WG} \tag{2}$$

If N_{WG} is large, the start and end times of a WPP shutdown becomes earlier, and consequently less energy production is inevitable. Thus, in this paper the smallest integer satisfying (2) is chosen as N_{WG}.

On the other hand, once N_{WG} is determined, R_{WG} is obtained by substituting N_{WG} into (1).

B. Determination of shutdown start- and end-times of each group

Fig. 2 shows the flowchart of the proposed algorithm. If v measured at a WM exceeds the cut-out speed, usually 25 m/s, the wind-arrival times ($T_{i,j}$) from the wind front detected at the WM to each WG are calculated. To calculate $T_{i,j}$, the distance ($s_{i,j}$) from the wind front passing the WM to each WG should be calculated first. From Fig. 3, the distance ($s_{1,1}$) from the wind front to the nearest WG can be calculated by:

$$s_{1,1} = d_m \times (1 + \tan\alpha) \times \cos\alpha \tag{3}$$

For the first line of WGs, the distances $s_{1,j}$ are calculated as:

$$s_{1,j} = s_{1,1} + (j-1)d \times \sin\alpha, \qquad j = 2, \cdots, n \tag{4}$$

The distances for all the following WGs are calculated by:

$$s_{i,j} = s_{(i-1),j} + d \times \cos\alpha, \qquad i = 2,\cdots,n,\ j = 1,\cdots,m \tag{5}$$

Consequently, $T_{i,j}$ can be calculated by:

$$T_{i,j} = \frac{s_{i,j}}{v} \tag{6}$$

Then, a sequence of WGs is generated in the order of $T_{i,j}$ and subsequently a group sequence, which consists of N_{WG} WGs, is generated.

In the next step, the shutdown start- and end-times of each group are determined. To protect all WGs in a group from the storm, all WGs should be shut down before the wind front reaches the nearest WG in the group. Hence, the shutdown end-time ($T_{GN,end}$) of each group is determined as the minimum $T_{i,j}$ in the group. Then, the shutdown start-time ($T_{GN,start}$) of each group is determined by subtracting the duration time (t_{down}) of the WG shutdown from $T_{GN,end}$:

$$T_{GN,start} = T_{GN,end} - t_{down} \tag{7}$$

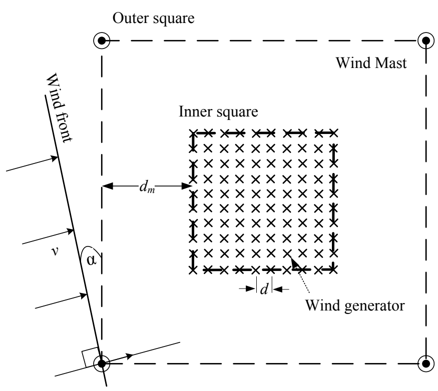


Fig. 1. Configuration of a WPP.

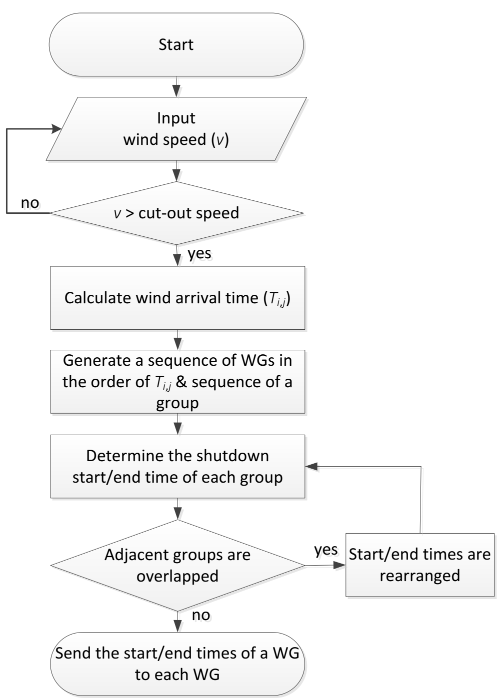


Fig. 2. Flow-chart of the proposed algorithm.

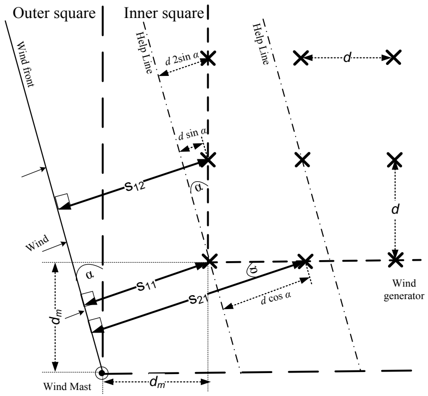


Fig. 3. Distance from the wind front passing a WM to each WG.

In this paper, t_{down} is obtained by dividing the rated power of an individual WG by R_{WG}. As explained in Subsection II-A, t_{down} is the smallest because the largest R_{WG} is chosen. Thus, more energy production is possible.

If the shutdown start-time ($T_{GN,start}$) of a group and the shutdown end-time ($T_{G(N-1),end}$) of the preceding group are overlapped, $T_{G(N-1),start}$ and $T_{G(N-1),end}$ of the preceding group are advanced by considering the overlapped time. Finally the start/end times of a WG are sent to each WG.

III. CASE STUDIES

The description of the studied WPP is shown in Table I. The top 2 operational off-shore WPPs are Walney and Thanet, which are composed of 102 WGs and 100 WGs, respectively [13, 14]. Hence, the inner square composes 100 WGs in this paper (10 rows and 10 columns). The rated power of each WG is 5 MW. The distance (d) between two adjacent WGs is 1 km. Four WMs are positioned at the edges of the outer square. The direct distance (d_m) between the inner square made by the WPP and the outer square made by WMs is 11.4 km [11].

Meanwhile, the ramp rate of the British Grid Code (R_{GC}) is 10% of the rated output per minute i.e., 50 MW/min [9]. In this paper, the maximum R_{WG} is set to be 500 kW/s because the speed of controlling the pitch angle is 8–10°/s [15–17] and thus more than 10 seconds are required to shut down an operating WG without using a brake.

N_{WG} is set to two by using (2) and corresponding R_{WG} is set to 415 kW/s from (1). Finally, t_{down} becomes 12.05 s, which is the minimum shutdown duration without using a brake.

The proposed algorithm depends on the wind direction and speed. Thus, this paper investigates the effects of the two factors on the performance of the algorithm.

TABLE I
DESCRIPTION OF THE STUDIED WPP

Wind power plant model	Value
Total installed capacity of the WPP, 100×5 MW	500 MW
Distance between two adjacent units, d	1 km
Direct distance between the inner square and the outer square, d_m	11.4 km
Ramp rate requirement of the UK Grid Code, R_{GC}	50 MW/min

In cases 1–3, the performance of the proposed algorithm is compared with a conventional algorithm [11, 12] by varying the wind speed and direction in terms of maximum ramp rate, mismatching time, required reserve power, and energy production. Figs. 4a–6a represent the power outputs of the WPP during the shutdown. Figs. 4b–6b show the ramp-down rates of the WPP and the ramp rate of a grid code, which is converted from minutes to seconds, 830 kW/s. In each figure, the dotted and the thick lines represent the results using a conventional algorithm and the proposed algorithm, respectively.

A. *Effects of the wind direction*

Case 1: wind speed of 30 m/s, wind direction of 0°

Fig. 4 shows the results for case 1. In this case, the wind-arrival time from the WM to the last WG in the WPP is 680 s. For no WPP shutdown, the shutdown process of WGs starts 380 s after the storm arrived at a WM. The output of the WPP is reduced by 50 MW every 25 s and thus the average ramp rate of the WPP is 1,667 kW/s, which is twice larger than R_{GC}. This poses a hard task on the power grid as it has to compensate the deficit power due to the WPP shutdown. For the conventional WPP shutdown, the shutdown starts as soon as a storm is detected and the shutdown duration time of a WG is set to the minimum wind-arrival time of 380s, which is 31 times larger than the minimum shutdown duration time. The ramp-down rate remains small immediately after the storm reaches the WM, but increases as time goes on. It starts to exceed R_{GC} at 200 s and remains large over R_{GC} for 280 s. However, for the proposed algorithm, the shutdown starts 77 s after storm detection and the ramp-down rate keeps R_{GC} at all times.

Table II shows the comparison results for case 1. The energy productions of the conventional and proposed algorithm after the storm detection are 47.15 MWh and 52.54 MWh, respectively whilst the energy production for no WPP shutdown is 73.51 MWh. The energy production with the proposed algorithm is about 11% more than that with the conventional algorithm. On the other hand, a deficit power of 83.39 MW should be prepared by the power grid for the conventional shutdown whilst no power is necessary for the proposed algorithm. The results indicate that the proposed shutdown algorithm always meets the R_{GC} even in the case of the WPP shutdown in storm-driven situations and produces more energy than the conventional one.

Case 2: wind speed of 30 m/s, wind direction of 45°

Fig. 5 shows the results for case 2. In this case, the wind-arrival time from the WM to the last WG of the WPP is 962 s, which is longer than in case 1 because the wind direction is 45°. For no WPP shutdown, the shutdown starts 537 s after storm detection. In this case, the magnitudes of the step are different unlike case 1 because the magnitude of the step change varies the number of the WGs shut down simultaneously due to the wind direction of 45°. The average ramp-down rate of the WPP is 1,176 KW/s, which is 1.4 times larger than R_{GC}. The conventional algorithm starts the shutdown as soon as the storm is detected. The shutdown duration time of a WG is set to the minimum wind-arrival time of 537s, which is 41% larger than case 1. The maximum ramp rate in case 2 is smaller than that in case 1 due to the increased shutdown duration time. The proposed algorithm starts the shutdown 324 s after the storm has been detected and the ramp-down rate keeps R_{GC} at all times as in case 1. However, the ripple of the ramp-down rate for the proposed algorithm is shown around the end of shutdown because the ramp-down rate keeps zero between the adjacent two groups for more production of energy.

Table III shows the comparison results for case 2. The energy production of the proposed algorithm after storm detection is 86.82 MWh, i.e., 30% larger than the conventional one because the shutdown duration in case 2 is increased due to the wind direction of 45°. However, deficit power in case 2 is 21.51 MW, i.e., about a quarter of that in case 1 due to the increase in the shutdown duration. The results indicate that the proposed algorithm meets the R_{GC} at all times and produces more energy than the conventional one even for the shutdown with different wind direction.

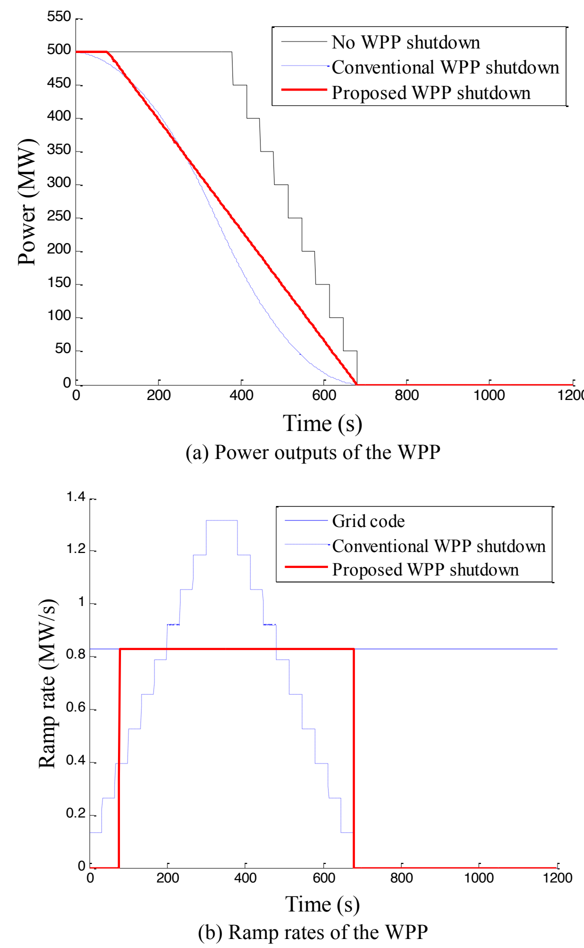
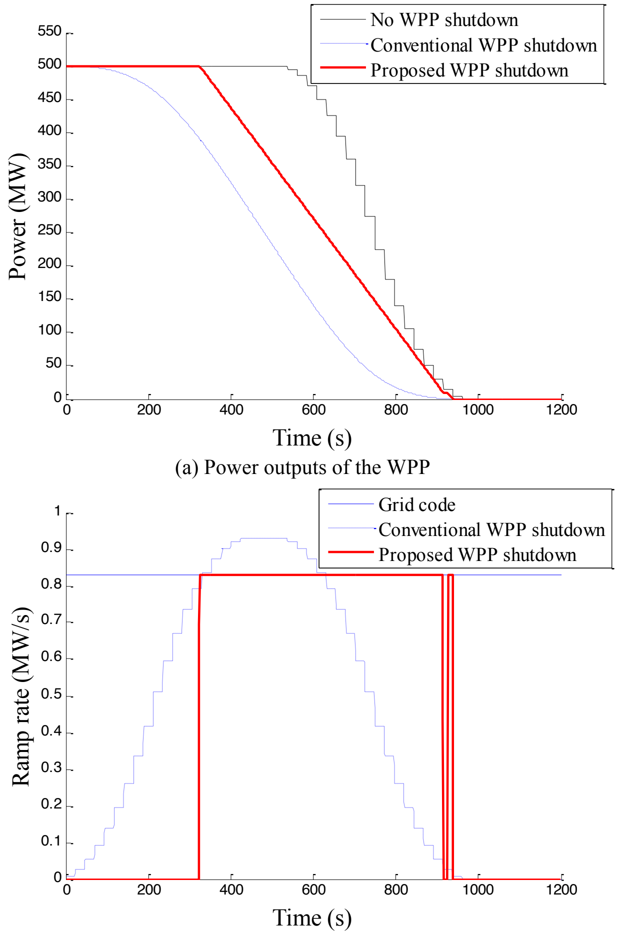


Fig. 4. Results for case 1.

TABLE II
COMPARISON RESULTS FOR CASE 1

	No WPP shutdown	Conventional WPP shutdown	Proposed WPP shutdown
Maximum ramp rate (MW/s)	-	1.32	0.83
Mismatching time (s)	-	280	0
Required reserve power (MW)	-	83.39	0

Energy production (MWh)	73.51	47.15	52.54



(a) Power outputs of the WPP

(b) Ramp rates of the WPP

Fig. 5. Results for case 2.

TABLE III
COMPARISON RESULTS FOR CASE 2

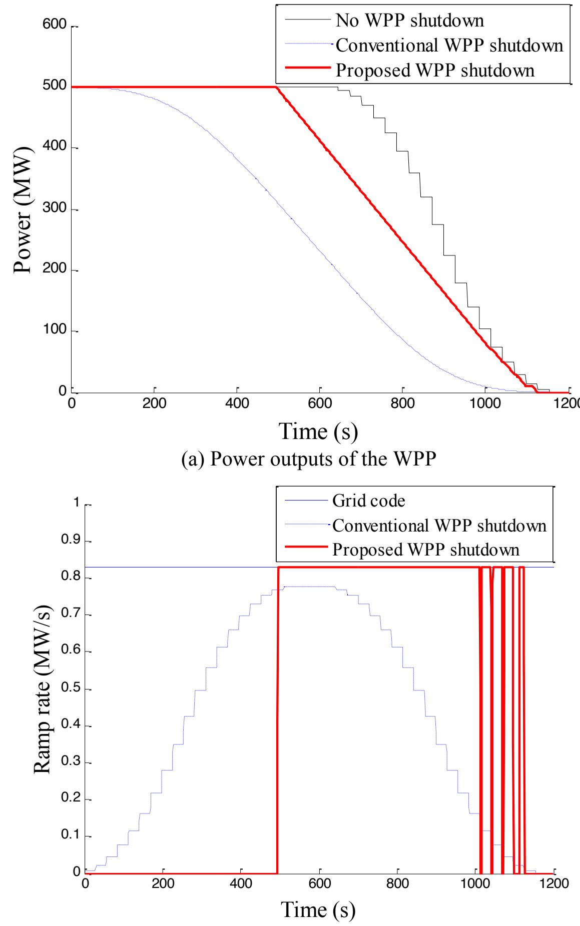
	No WPP shutdown	Conventional WPP shutdown	Proposed WPP shutdown
Maximum ramp rate (MW/s)	-	0.93	0.83
Mismatching time (s)	-	301	0
Required reserve power (MW)	-	21.51	0
Energy production (MWh)	104.03	66.71	86.82

B. *Effects of the wind speed*

Case 3: wind speed of 25 m/s, wind direction of 45°

Fig. 6 shows the results for case 3. In this case, the wind-arrival time from the wind front to the last WG of the WPP is 1,154 s, which is larger than cases 1 and 2 due to the smaller wind speed. For no WPP shutdown, the shutdown starts 644 s after the storm is detected at a WM. For the conventional algorithm, the shutdown starts as soon as a storm is detected. The duration time of a WG shutdown is 644 s. In this case the ramp-down rate does not exceed R_{GC} because the shutdown duration becomes large due to the smaller wind speed. For the proposed algorithm, the shutdown starts 494 s after storm detection.

Table IV shows the comparison results. The conventional and proposed algorithm meets the grid code requirement. However, the proposed algorithm produces 110.67 MWh, which is 38% greater than the conventional one.



(a) Power outputs of the WPP

(b) Ramp rates of the WPP

Fig. 6. Results for case 3.

TABLE IV
COMPARISON RESULTS FOR CASE 3

	No WPP shutdown	Conventional WPP shutdown	Proposed WPP shutdown
Maximum ramp rate (MW/s)	-	0.78	0.83
Mismatching time (s)	-	0	0
Required reserve power (MW)	-	0	0
Energy production (MWh)	124.86	80.07	110.67

IV. CONCLUSIONS

This paper proposes an off-shore WPP shutdown algorithm to meet the required ramp rate of a grid code in a storm-driven situation without using a brake. The proposed algorithm determines the number of WGs to shut down simultaneously to meet the grid code requirement and employs the minimum shutdown duration instead of the minimum wind-arrival time to maximize the energy production without using a braking system. Based on the wind information measured at a WM, wind-arrival times from the WM to each WG are calculated and a sequence of WGs is generated in the order of wind-arrival times to each WG. Then, the group sequence, consisting of the predetermined number of WGs, is generated. The start/end times of each group are calculated by considering the wind-arrival time and the shutdown duration. If the shutdown start/end times of adjacent groups are overlapped, the shutdown start/end times of the preceding group are re-scheduled.

The performance of the proposed algorithm is verified under various storm conditions by varying the direction and speed of wind. In addition, the comparison results with the conventional one are presented. The proposed algorithm starts shutdown as late as possible by considering the minimum shutdown duration whilst the conventional shutdown algorithm starts shutdown immediately after a storm is detected. That is why the algorithm could produce more energy during the shutdown.

The advantages of the proposed algorithm lie in the fact that it can not only shut down the WPP without exceeding the required ramp rate of a grid code, but also maximize the wind energy production during the shutdown even in a storm-driven situation.

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