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Dynamic adaptation of Active wake control

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Abstract

Active Wake Control is an approach of operating wind farms in such a way as to maximize the overall wind farm power production. It consists of two concepts: pitch-based Active Wake Control (called Heat & Flux), and yaw-based Active Wake Control (called Controlling Wind). ECN holds patents for both approaches.

This report describes the effects of time-variations in the wind speed and direction on the benefits from Active Wake Control, and provides recommendations on how to implement Active Wake Control in the field to achieve a good balance between power production gain and actuator duty increase.

It has been concluded that Controlling Wind, when applied on real-life time-varying wind data, results in an increase of the yaw actuator duty by a factor of 5 to 15 (depending on the selected adaptation strategy). These actuator duties, however, are not representable for the complete lifetime but only for the considered wind conditions. Furthermore, depending on the adaptation strategy, the loss of Active Wake Control benefit varies between 10 and 60%! A balanced Controlling Wind adaptation strategy is proposed that keeps the loss of Active Wake Control benefit at about 35% at a yaw actuator duty increase by a factor of 8. However, this increase is only valid for a few wind directions and wind speeds; the lifetime yaw actuator duty is expected to increase by less than 1%. More extreme adaptation strategies are also proposed.

Heat & Flux, on the other hand, does not lead to a noticeable increase of the pitch actuator duty, which remains below the 0.5 degrees per minute for all considered strategies. The loss of benefit is also much smaller: up to 20%. Surprisingly, one of the investigated adaptation strategies was able to achieve the same power output as an instantaneous adaptation of the Heat & Flux pitch angle offset (i.e. the theoretical limit), and since the pitch duty is too small to be irrelevant here, this is also the recommended strategy.

Contents

1

Introduction

Active Wake Control (AWC) is a concept to operate wind farms in an economically optimal manner, offering the following user benefits:

- Maximize the wind farm power production
- Reduce O&M costs by minimizing the fatigue loading
- Allow for reduction of CAPEX by placing the turbines closer (reduce electrical infrastructure costs) when applied at the design phase of the wind farm.

The AWC concept is applicable at below rated wind speeds, and consists of two strategies that can either be applied individually or in combination:

- Pitch-based AWC (also known as Heat & Flux) [2]: The pitch angles of the upstream wind turbines are increased (or the active power set-point is decreased) to increase the wind speed and reduce the turbulence intensity in the wake.
- Yaw-based AWC (also known as Controlling Wind) [1]: Upstream wind turbines are operated with rotor yaw misalignment to divert their wakes away from the downstream wind turbines.

Different feasibility studies in which the AWC settings (pitch and yaw angles) have been optimized using FarmFlow simulations indicate that a significant increase of the lifetime power capture might be possible. However, all of these results have been obtained using FarmFlow simulations which are static with respect to the free incoming wind resource (i.e. the undisturbed wind field has a constant speed and direction).

In a field implementation, the wind speed and direction will of constantly vary significantly, and so the following question arises:
How should AWC be dynamically adapted to achieve an optimal balance between the benefit and the resulting actuator duty?
This report aims at answering this question.

2

Approach

As explained in the introduction, this study investigates, (1), the effect of time-variations in the wind speed and direction on the benefits of AWC, and (2), how to adapt the AWC settings in such a dynamic environment. This is to be investigated for both Heat & Flux and Controlling Wind.

To this end, a simple setup is considered consisting of a single row of seven wind turbines, the first six at distances of around 7D, and the last one at 15D (a row of an existing wind farm). As the purpose is to study the effects of time-variations in the wind on the power production with AWC, it suffices to focus on just one row of turbines and to consider only a sector of wind directions around the orientation of the row of turbines. Therefore, following approach has been used (Active Wake Control below refers to either Heat & Flux or Controlling Wind)

Active Wake Control optimization First, AWC is optimized for a sector of wind directions (258 to 281 degrees) around the direction of the row (269.5 degrees), and wind speeds 6-10 m/s. Heat & Flux is applied only to the first turbine in the row, while Controlling Wind is applied to all turbines but the last one. The optimal AWC settings for Heat & Flux and Controlling Wind for the first wind turbine in the row and for the considered wind speeds and directions are given by the dashed curves on Figure 1. The different curves represent the results for different mean wind speeds (see legends). Notice that the optimal settings are not smooth functions of the wind, especially those for Heat & Flux. This is caused by the numerical nature of the optimization and the very low sensitivity of the solution around the optimum.

Smooth the optimal AWC settings The optimal Active Wake Control settings, given by the dashed lines in Figure 1, clearly need to be smoothed before implementation in the field, especially the results from the Heat & Flux optimization (left plot). Analysis of these results have indicated that in the optimal settings no clear trends can be observed with respect to the wind *speed* variations, while there are clear trends visible with respect to the wind *direction*. Therefore, it has been decided to approximate the optimal Active Wake Control settings by smooth curves that only depend on the wind direction, and not on the wind speed. These approximations are given by the thick black curves in the two plots on Figure 1. The curve approximating the optimal

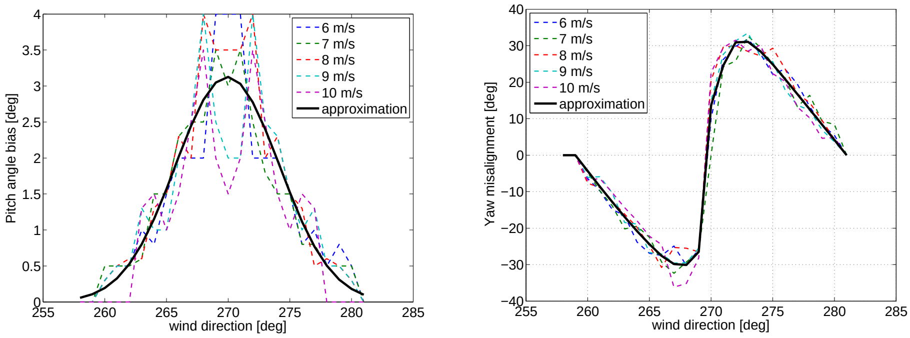

Figure 1: Active Wake Control settings

Heat & Flux settings is obtained by fitting a Gaussian curve to the settings averaged over the wind speed. For Controlling Wind, the approximated curve is constructed by fitting two third order Bezier curves (one for the positive, and one for the negative yaw misalignments) to the Controlling Wind settings averaged over the wind speeds; this, however, is done for both the the first turbine (given in the right hand side plot in Figure 1) and the next to last one (not plotted), since the settings of the remaining turbines are obtained by linear interpolation of those.

Quantization of Active Wake Control settings To analyze the effect of time-vqrying wind resource on the benefits from Active Wake Control it is necessary to be able to calculate the power production based on time-series of wind speed and wind direction, while the Active Wake Control settings are being slowly adapted to the changing wind. As such dynamic simulations cannot be performed with ECN's software FarmFlow, we will use static simulations performed at different wind speeds, directions and yaw misalignment, and process these to approximate the outcome of a dynamic simulation. In order to limit the number of FarmFlow simulations, it is decided to choose a discrete set of Active Wake Control settings (quantization) for which simulations are performed for all considered wind speeds and directions (see below). For Heat & Flux a total of 6 pitch angle offsets are chosen (0:0.4:3.2 degrees), while for Controlling Wind the number of yaw misalignments is 16 (larger since there are positive and negative values).

FarmFlow simulations Simulations are performed with FarmFlow for wind speeds of 6 to 10 m/s, wind directions of 258 to 281 degrees, and the selected Active Wake Control settings at the quantization step (so both for Heat & Flux and Controlling Wind). The power productions under all these conditions are stored in lookup tables for use in the dynamic simulation.

Dynamic simulation setup To investigate the effects of time variations in the wind resource on the performance of Active Wake Control, it is necessary to perform dynamic simulations. As already mentioned, this is not possible with FarmFLow. To approximate such a dynamic simulation, the lookup tables described above are fed with real-life wind data, obtained from metmast 3 at ECN's test site in Wieringermeer. The wind data used is collected at a height of 80 m, is sampled at 10 seconds and has duration of 5 years (2008 to 2012). Out of these data all time intervals are extracted with duration of at least 1000 seconds, and containing wind speed signals between 6 and 10 m/s and wind direction that remains within an interval of 20 degrees. The selected batches, therefore, do not necessarily contain the wind directions considered in the FarmFlow simulations described above, since otherwise insufficient amount of data would have remained for the analysis.

Each of these data batches is used to feed the simulation, depicted in Figure 2. The original wind speed and direction signals are first down-sampled (after applying anti-aliasing filtering) to a sample rate that is considered more reasonable for the purpose here (studied sample rates: 30 and 60 sec). The resampled wind direction signal is then used to obtain the Active Wake Control settings, which are next used to feed the power production lookup table to get the power production as function of time. As can be seen from the figure, two cases are simulated (see signal flows on top and bottom): one where the Active Wake Control settings are adapted immediately based on the incoming wind direction (giving the theoretical limit on the achievable performance), and another one where the wind direction is first processed (see below) before the Active Wake Control settings are obtained (as in a real-life implementation). In both cases the power productions are calculated and compared. This allows to analyze the loss of benefit due to the necessary processing of the wind direction signal before the determination of the Active Wake Control settings.

Filtering In a real-life implementation, the AWC settings will not be adapted instantly, but based on low-pass filtered wind direction signal. To keep the phase shift minimal, a second order elliptic filter is used with 1dB ripple and 20 dB reduction. Different cutoff frequencies are studied in the range between 1/60 Hz and 1/1200 Hz. The low-pass filtered wind direction is also down-sampled to avoid that the Active Wake Control algorithm modifies the turbine settings too often.

Hysteresis (Only applicable for Controlling Wind) The form of the curve defining the Controlling Wind yaw misalignment as function of the wind direction (see the left plot in Figure 1) is such that small changes in the wind direction around 270 degrees can lead to huge changes in the yaw misalignment setpoint. To reduce the yaw actuator duty somewhat in situations where the wind direction varies around the direction of the row of wind turbines, hysteresis is applied on the (filtered) wind direction signal before the Controlling Wind settings are determined. The hysteresis is activated when the difference between the row orientation and the filtered wind direction drops below 1 degree, and deactivated when this difference increases above 2 degrees. When active, the outputs of the hysteresis is kept constant equal to the direction of the row of turbines (which will give rise to a zero yaw misalignment setting), while when inactive it passes through the wind direction input unmodified.

AWC settings determination The wind direction signal to which filtering (and in case of Controlling Wind also hysteresis) is applied is used to determine the Active Wake Control settings (using the smooth black curves in Figure 1).

Power production calculation The unfiltered (but down-sampled) wind speed and direction, together with the Active Wake Control settings, are used as input to the lookup tables. Using 3D interpolation, the power productions are calculated for each time instant for both the case of instantaneous and dynamic adaptation of the Active Wake Control settings. The relative decrease in the produced energy by the dynamic adaptation strategy with respect to the instantaneous one is calculated.

Yaw actuator duty (Only applicable for Controlling Wind) While Heat & Flux is expected to have negligible effect on the pitch actuator duty, the effect of Controlling Wind on the yaw actuator will be significant. To study that effect, a simple (but realistic)

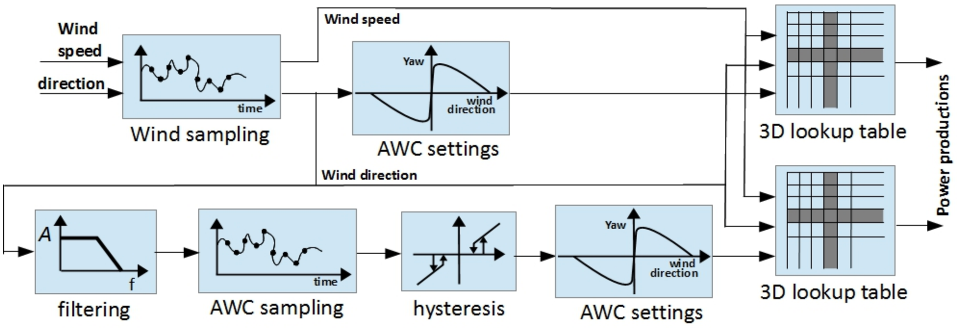

Figure 2: Active Wake Control dynamic simulation setup

yaw control model has been implemented (not shown in Figure 2). The actuator control model receives as input the wind direction (the one after the sampling block in Figure 2) and the yaw misalignment setpoint, and controls the yaw orientation of the nacelle by either keeping it constant or turn it at the maximum speed of 0.1 degrees/s (notice that at this speed it takes 10 minutes to rotate the nacelle by 60 degrees, moving from maximal positive to maximal negative yaw misalignment; see Figure 1). The yaw control acts on the error between the yaw orientation of the nacelle en the yaw setpoint (being formed as the sum of the wind direction and the yaw misalignment setpoint). It activates the yaw motor when the 30-sec averaged error exceeds 8 degrees, and deactivates it when the 60-min averaged error signal drops below 4 degrees. Based on this model, the yaw actuator activity is calculated as the relative amount of time that the yaw actuator is active.

3

Results

3.1 Controlling Wind

This section presents the results from the analysis of different strategies for online adaptation of the yaw misalignment settings on the benefits from Controlling Wind, as well as on the resulting actuator duty. Following the approach described in Chapter 2, the following strategies have been considered:

Filtering With respect to the low-pass filtering, applied to the wind direction signal (see Figure 2), the following scenarios have been considered:

- Fast filtering: the cutoff frequency of the filter equals half of the sampling frequency at which the Controlling Wind settings are updated (see below)
- Slow filtering: the cutoff frequency equals 1/1200 Hz, and is independent on the sampling frequency at which the Controlling Wind settings are updated

Sample frequency This is the frequency at which the Controlling Wind settings are updated, which should clearly be lower than the sample frequency of the wind signal (1/60 Hz). Thee following sampling frequencies are considered: 1/60, 1/120, 1/300, 1/600 and 1/1200 Hz, i.e. sample times between 1 and 20 minutes.

Hysteresis Two cases considered: with and without hysteresis.

All possible combinations of filtering, sampling frequency and hysteresis, have been considered (besides the combination of slow filtering and sample frequency of 1/1200 Hz, which makes no sense) and simulated using the wind data descried in Chapter 2. The results are summarized in Figure 3 depicting the loss of power gain versus the yaw actuator duty increase factor. The loss of power gain is expressed as the relative decrease of power production with dynamic adaptation of the Active Wake Control settings with respect to the power production with instantaneous adaptation. The yaw actuator duty increase factor is calculated as the relative increase of the amount of time that the yaw actuator is active under dynamic adaptation of the Active Wake Control settings with respect the reference case without Active Wake Control.

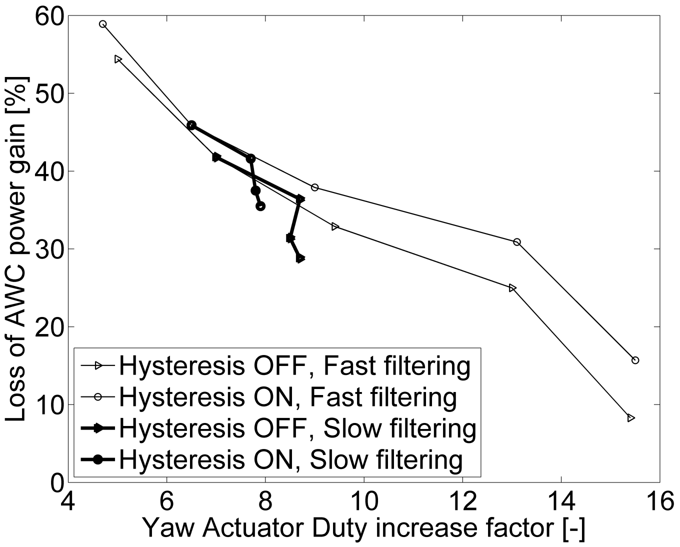

Figure 3: Influence of different strategies for dynamic adaptation of the Controlling Wind settings on the benefits and the yaw actuator duty

Four different lines can be seen in Figure 3, representing the different combinations of filtering (slow/fast) and hysteresis (off/on). The thick lines represent the cases with slow filtering, while the thin ones - with fast filtering. The lines with the circle markers correspond to the case when the hysteresis is active, and those with triangle markers – no the case without hysteresis. The different points on these lines are obtained for the different sampling frequencies for the Active Wake Control adaptation: The lower the sampling frequency, the lower the yaw actuator duty increase, and the higher the loss of Active Wake Control benefit. That is, the lowest point of each of these curves corresponds to a sampling frequency of 1/60 Hz, the frequency decreasing towards 1/1200 Hz as you go up the curves.

The following conclusions can be drawn from these results:

- the yaw actuator duty increases significantly due to the dynamic adaptation of the Controlling Wind settings as compared to the case without Controlling Wind: the figure indicates increase of the yaw actuator duty by a factor of 5 to 15!

- the loss of Active Wake Control benefit can vary between 10 and 60%, depending on the choice of filtering and sampling frequency. As expected, the loss in benefit reduces when the yaw actuator activity increases. Generally, the conclusion can be drawn that by allowing an increase of the yaw actuator duty by a factor of 8, the loss of benefit can be kept at around $1/3$ or so. This is achieved, for instance, by using hysteresis and applying a filter with cutoff frequency of 1/1200 Hz (slow filter) and sampling frequency of 1/60 seconds

- slower filtering significantly reduces the amount of yaw actuator duty (compare the right-most points of the thick and thin curves). Moreover, when slow filtering is used, the sampling frequency has only small effect on the yaw actuator duty, but relatively large effect on the loss of benefit. It is therefore recommended to use the fastest sample time in this case (60 seconds).

- the use of hysteresis results in only small reduction of the yaw actuator duty, while at the same time the loss of benefit increases. However, hysteresis might prove more useful in the case when the average wind direction is by a few degrees away with respect to the orientation of the row of turbines, so it is recommended to keep it in a final implementation.

In summary, the following strategies are suggested:

Balanced Controlling Wind strategy: Hysteresis on, cutoff frequency 1/1200 Hz, sample frequency 1/60 Hz. This results in yaw actuator duty increase by a factor of 8, and a decrease of the benefit from Active Wake Control by about 35.5%.

High benefit Controlling Wind strategy: Hysteresis off, cutoff frequency 1/120 Hz, sample frequency 1/60 Hz. This results in yaw actuator duty increase by a factor of 15.4, and a decrease of the benefit from Active Wake Control by 8.3%.

Low loading Controlling Wind strategy: Hysteresis on, cutoff frequency 1/2400 Hz, sample frequency 1/1200 Hz. This results in yaw actuator duty increase by a factor of 4.7, and a decrease of the benefit from Active Wake Control by 58.9%.

Notice that results related to the actuator duty increase are not representable for the whole lifetime, but only for that part of it corresponding to the considered wind directions and below rated wind speeds, say about 10% of the time. Moreover, only the leading turbine is considered; the downwind turbines receive smaller yaw misalignment settings and, therefore, will need less yaw actuator duty to realize it. Therefore, the lifetime yaw actuator duty is expected to increase by less than 1%.

3.2 Heat & Flux

This section presents the results from the analysis of different strategies for online adaptation of the pitch angle offset on the benefits from Heat & Flux, as well as on the resulting pitch actuator duty. Following the approach described in Chapter 2, the following strategies have been considered:

Filtering With respect to the low-pass filtering, applied to the wind direction signal (see Figure 2), the following scenarios have been considered:

- Fast filtering: the cutoff frequency of the filter equals half of the sampling frequency at which the Heat & Flux settings are updated (see below)
- Moderate filtering: the cutoff frequency equals 1/600 Hz
- Slow filtering: the cutoff frequency equals 1/1200 Hz

Sample frequency This is the frequency at which the Heat & Flux settings are updated, which should clearly be lower than the sample frequency of the wind signal (1/60 Hz). Thee following sampling frequencies are considered: 1/60, 1/120, 1/300, 1/600 and 1/1200 Hz, i.e. sample times between 1 and 20 minutes.

Hysteresis No hysteresis is considered with Heat & Flux.

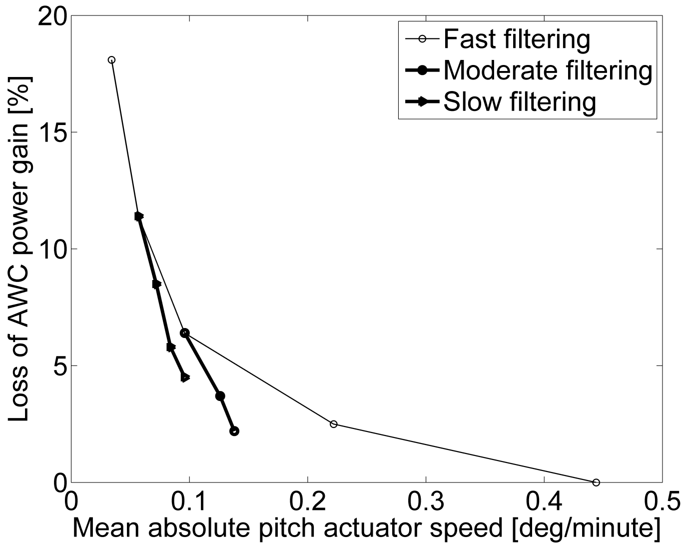

Figure 4: Influence of different strategies for dynamic adaptation of the Heat & Flux settings on the benefits and the pitch actuator duty

All possible combinations of filtering and sampling frequency have been considered (besides the cases when the filter cutoff frequency is higher than half the sample frequency) and simulated using the wind data described in Chapter 2. The results are summarized in Figure 4 depicting the loss of power gain versus the pitch actuator duty. The loss of power gain is expressed as the relative decrease of power production with dynamic adaptation of the Active Wake Control settings with respect to the power production with instantaneous adaptation. The pitch actuator duty is calculated as the mean value of the absolute pitch actuator speed under dynamic adaptation of the Active Wake Control settings.

The following conclusions can be drawn from these results:

- the pitch actuator activity due to Heat & Flux is negligible (below 0.5 degrees *per minute*), and is hence not seen as important factor for consideration when selecting the Heat & Flux strategy.
- the loss of Active Wake Control benefit is much more moderate than was the case with Controlling Wind, which now remains well below 20% for all considered strategies. Even more interesting: it appears to be possible to implement Heat & Flux in such a way that no benefit is lost with respect to the theoretical optimum obtained with instantaneous adaptation of the Heat & Flux pitch angle.
- The slower the filtering, the less the pitch actuator duty, but also the less performance is achievable in terms of loss of Heat & Flux benefit.

Therefore, the following Heat & Flux adaptation strategy seems the best choice:

Heat & Flux strategy: Cutoff frequency 1/120 Hz and sample frequency 1/60 Hz. This results in no decrease of the benefit from Active Wake Control.

4

Conclusions

This report studies the question of how to adapt the Active Wake Control settings in the field so as to achieve an optimal balance between loss of Active Wake Control benefit in terms of power production on the one hand, and the actuator duty on the other. To this end, a simple simulation environment has been set up, using real-life wind data as input, and a lookup table obtained using FarmFlow simulations that contains the power productions under different conditions (wind speeds, wind directions, Heat & Flux pitch angle offsets and Controlling Wind yaw misalignment). Different strategies for adaptation of the Active Wake Control settings have been evaluated, containing the following elements: a low-pass filter acting on the wind direction signal, a sample-and-hold block (down-sampling), and a hysteresis.

With respect to Controlling Wind it has been concluded that Controlling Wind, when applied to real-life time-varying wind data, results in a large increase of the yaw actuator duty (5-15 times larger than the conventional actuator duty). These actuator duties, however, are not representable for the complete lifetime but only for the considered wind conditions (below rated winds and directions in a sector of 24 degrees). Furthermore, depending on the adaptation strategy, the loss of Active Wake Control benefit varies between 10 and 60%! A balanced Controlling Wind adaptation strategy is proposed that keeps the loss of Active Wake Control benefit at about 35% and the yaw actuator duty increase at a factor of 8. More extreme adaptation strategies are also proposed. This yaw actuator duty increase is however only representative for the considered wind directions and below rated wind speeds, which will constitute no more than about 10% of the lifetime. Moreover, the yaw actuator duty represents a worst-case value since it is calculated for the leading turbine only; the downwind turbines receive smaller yaw misalignment settings and, therefore, will need less yaw actuator duty to realize it. Therefore, the lifetime yaw actuator duty is expected to increase by less than 1%.

Heat & Flux, on the other hand, does not introduce noticeable increase of the pitch actuator duty, which remains below the 0.5 degrees per minute for all considered strategies. The loss of benefit is also much smaller: up to 20%. Surprisingly, one of the adaptation strategies was able to achieve the same power output as an instantaneous adaptation (i.e. the theoretical limit), and as the pitch actuator duty is small to be irrelevant, this is also the recommended strategy.

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