

# Review on Target Tracking of Wind Power and Energy Storage Combined Generation System

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**Abstract.** The utilization of large-scale renewable energy resources can effectively alleviate the shortage of traditional fossil fuel energy resources and the problem of environmental pollution. In order to realize the grid-friendly access of renewable energy power generation represented by wind power, it is necessary to involve energy storage, of which the battery energy storage is the most widely used type, and build a relatively controllable combined power generation system. Target tracking is one of the demand that wind power and energy storage combined generation system is supposed to meet. According to the discrepancies in tracking target, this paper firstly categorizes the target tracking issue into three parts, namely tracking wind power forecasting curve, tracking generation plan and tracking dynamic power generation index. Then based on the categories and considering their own research focuses, relevant literatures are summarized and compared. Conclusions and future research points are provided in the end. It is found that the issue of tracking dynamic power generation index worth more attention attributed to its novelty and complexity, where future work may be conducted from two aspects, the mathematical model dynamic power generation index and control strategy with overall management ability.

## 1. Introduction

The exploitation of renewable resources can effectively alleviate the shortage of traditional fossil fuel energy resources and the problem of environmental pollution. Power generation is a significant way of renewable resources utilization, represented by photovoltaic power generation and wind power generation, which has become a hot point in power and energy field.

China has a vast territory and abundant wind resources in the "Three-North Regions", providing the conditions to build large-scale wind power farms. The total grid-integrated capacity of China's wind power has reached 164 million kilowatts by 2017 [1]. However, the output characteristics of wind power differ from those of traditional power generation. The varying and stochastic nature of wind power can cause a series of problems when connected to the power grid, which hinders the full utilization and development of wind power to a certain extent, e.g. frequency problems, the frequent start-stop of the conventional unit and the increasing demand for the slope climbing ability of the regular units [2], [3]. Also, wind power is hard to be precisely forecasted, leading to difficulties in dispatch plan scheduling and executing.



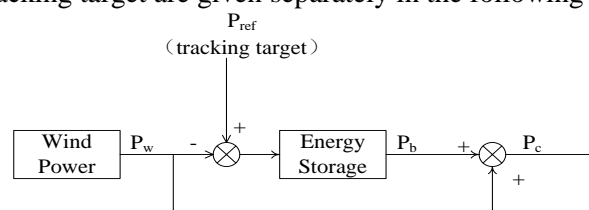
One of the most widely discussed and adopted solutions to the grid-connected problems of wind power is to form a relatively controllable wind power and energy storage combined power generation system. There exist various types of energy storage system, e.g. pumped storage power plant, mechanical energy storage, battery energy storage, and electromagnetic storage. Although pumped storage power plant is one of the earliest used energy storage system, its high demands for topography and water resources limit its application under some circumstances. As for mechanical energy storage, some progress has been made in the theoretical research on the combined operation of wind power and mechanical energy storage, the typical representatives of which are flywheel energy storage and compressed-air energy storage [4], [5]. However, the use of mechanical energy storage mainly remains in the stage of theoretical research and the application technology is not mature enough. Battery energy storage mainly includes lead acid battery, sodium-sulphur battery, lithium iron phosphate battery, etc [6], [7]. Battery energy storage is less limited by geographical location and easy to expand. In recent years, it has been suggested theoretically that the use of multi-type energy storage can solve the problem of renewable energy access, but multi-type energy storage has not been widely used because complex coordination problems and consistency problems remain unsolved in engineering application [8], [9]. Above all, the battery energy storage become noticeable in the engineering application of facilitating the wind power to form relatively controllable wind power and energy storage combined power generation system.

Smoothing generation output, peak and valley shaving, control of target tracking, and frequency adjustment are the four major modes of wind power and energy storage combined system [10]-[12]. They are all crucial to the normal operation of the wind power and energy storage combined system, as well as to ensure the safety and economy of power system.

This paper focuses on the reviewing of wind power and battery energy storage combined system under target tracking mode. Firstly, literatures on target tracking issue are categorized into three parts, namely tracking wind power forecasting curve, tracking generation plan, tracking dynamic power generation index. Then the discrepancies of the three items are summarized. Section 2.1 reviews the literatures on tracking wind power forecasting curve and introduces the criteria of assessment. Section 2.2 reviews the literatures on generation plan tracking, with control strategies in these literatures summarized, categorized and compared. Section 2.3 introduces the connotation of dynamic power generation index, analyses the difficulties on tracking dynamic power generation index. Section 3 is about literatures exploring multi-mode coordinated optimization considering target tracking and mode switching, which try to furtherly make use of energy storage in the wind power and energy storage combined generation system. Finally, some conclusions and future work that is worthwhile to carry out are provided in Section 4.

## 2. Target tracking of wind power and energy storage combined generation system

Generally, the research contents of target tracking of wind power and energy storage combined generation system can be expressed as follows: determine the amount of active power released by energy storage based on the deviation between the wind power and the target that the combined system is supposed to follow, with the control strategy and the state of charge (SOC) being considered (see figure 1). At present, there is no uniform definition of the research content of target tracking. In the light of the discrepancies in tracking target, this paper firstly categorizes the target tracking issue into three parts, namely tracking wind power forecasting curve, tracking generation plan, tracking dynamic power generation index, which is summarized and compared in table 1. Review on the literatures on the three tracking target are given separately in the following subsections.



**Figure 1.** Target tracking of wind power and energy storage combined system

**Table 1.** Categories of target tracking of wind power and energy storage combined system

Tracking Target			Aims of tracking
Item	Source of data	Characteristic	
Wind power forecasting curve	Wind power forecasting system	A fixed curve	Reducing wind power forecast error Meeting the criteria of assessment
Generation plan	Power system dispatching organisation	A fixed curve	Ensuring the reliable execution of generation plan
Dynamic power generation index	Power system dispatching organisation	A set of curves	Ensuring the reliable execution of dynamic power generation index

### 2.1. Tracking wind power forecasting curve

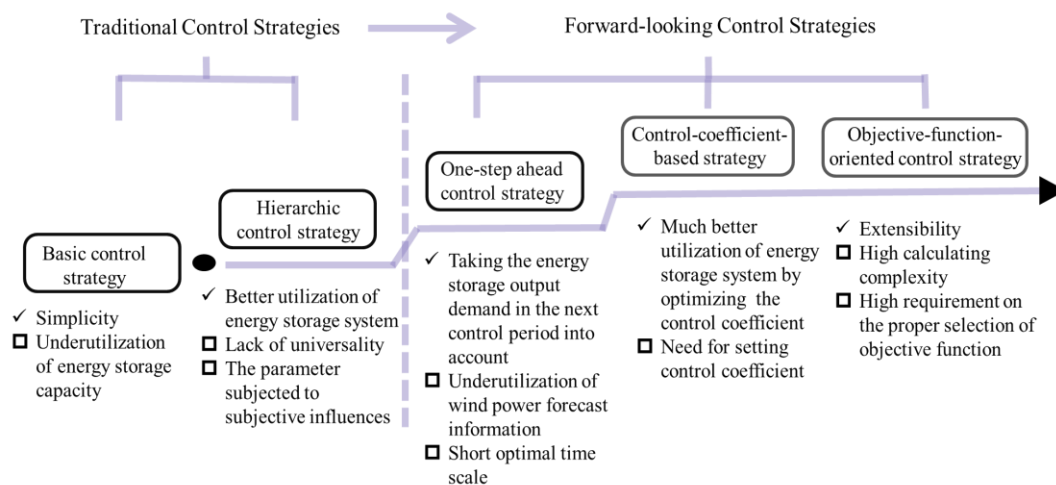
Researches on tracking wind power forecasting curve aim to meet the criteria of assessment. Take China for example, the criteria of assessment is issued by National Energy Administration of China in July 2011, called The Interim Management Measures for the Power Forecast of Wind Power Farms (hereinafter referred to as The Interim Management Measures), where it is stipulated that the maximum error of the daily prediction curve provided by the power forecast system of wind farm is not more than 25%, the real-time prediction error is not more than 15%, and the root mean square error (RMSE) of the full day forecast results should be less than 20% [13], [14]. If a wind farm fails to meet the accuracy rate and qualified rate, it would be punished.

Researches prove that energy storage can facilitate the wind power to meet the criteria in The Interim Management Measures [14]. For example, in the calculating example of literature [15], with the participation of energy storage, the qualified rate rises from 43.8% to 100% and the RMSE is within the limit.

### 2.2. Tracking generation plan

The generation plan, provided by the power system dispatching organization, is the reference curve for power generation. In terms of tracking generation plan, wind power generation performs worse than the conventional unit due to the volatility and intermittency of its output. Thus, energy storage is required to facilitate the wind power in tracking generation plan [16].

Numerous literatures taking the generation plan as the tracking target of wind power and energy storage combined system are available, majority of which concentrate on the studies of control strategies. The commonly-used control strategies are summarized in figure 2, with their pros and cons listed and relationships among them presented.

**Figure 2.** Four categories of control strategies commonly used in tracking generation

Traditional control strategies of wind power and energy storage combined system usually make decisions based on current operating conditions. Basic control strategy is one of the earliest adopted strategies in generation plan tracking of wind power and energy storage combined system. All the strategies to be introduced latter are improvements on the basis of the basic strategy. On the premise of satisfying the energy storage constraint, the strategy uses the bidirectional output ability of energy storage to compensate the deviation between the wind power and power generation plan in a control interval. To be more specific, the energy storage will be charged during the control intervals when wind power excess the generation plan, and be discharged in the opposite case. Otherwise, it does not participate in the tracking process. Basic control strategy is easy to implement. With this control strategy, the wind power and energy storage combined system performs well in tracking the generation plan. The simulation results in [16] showed that a satisfying performance in tracking the generation plan could be achieved if energy storage capacity is up to 15% to 25% of the wind farm capacity. Concerning the demand on prolonging service life of battery energy storage, basic control strategy sets a fixed limitation for the SOC (The upper limit varies from 0.8 to 1 while the lower limit varies from 0.1 to 0.2 in different literatures), and the battery energy storage can only operate in the case that its SOC is within the limitation interval. This way of SOC setting determines that in the case with basic control strategy, the deviation between the wind power and power generation plan is completely compensated or not a slightly compensated, which is not flexible and not conducive enough to make full use of the energy storage capacity. Therefore, some researches proposed hierarchic control strategy. Hierarchic control strategy improves the basic control strategy by refine the interval of SOC that the battery energy storage can operates, and gives more detailed rules. [17] is a typical literature that can be referred to, in which a sigmoid function is used to revise the degree of involvement of the energy storage. However, hierarchic control strategy is lack of universality and the performance varies in different cases.

Since traditional control strategies, represented by the basic strategy and hierarchic control strategy mentioned above, only consider current operating condition, and the combined generation system is not always equipped with sufficient capacity of energy storage, it is likely that the combined generation system is not able to tracking the generation plan curve continuously, and in some control intervals the deviation between the curve and the output of the combined generation system remains large [18]. Thus, it is necessary to design control strategies with overall management ability. On this background, efforts have been made by some researches and a series of forward-looking control strategies are put forward.

On the basis of short-term or ultra-short prediction values of wind power, the forward-looking control strategies arrange the timing and amount of energy storage charging or discharging in wind power and energy storage combined generation system in advance. The forward-looking control strategies can be categorized into one-step-ahead control strategy, control-coefficient-based strategy, and objective-function-oriented control strategy. One-step-ahead control strategy adjusts the current output of energy storage in the combined system by estimating the SOC at the end of next control interval and ensuring it is within the range of the limit interval. Literature [19] designed a series of adjustment rules, which is instructive for future studies. One-step-ahead control strategy is a primary forward-looking control strategy because it is short-sighted and does not make full use of the short-term or ultra-short prediction values of wind power. Control-coefficient-based strategy arrange the output of energy storage in advance of hours or a day by optimizing the energy storage charging or discharging power control coefficient indirectly. The key of the strategy lies in the setting of control coefficient. Literature [20] designed five control coefficients establishing the connections among the generation plan, the prediction value of wind power, the energy storage charge or discharge power and SOC of energy storage state. The five control coefficients are optimized by the particle swarm optimization algorithm in every rolling optimization period. Objective-function-oriented control strategy randomly select output of energy storage from the feasible interval to form a cluster of energy storage output sequence, and then under the guidance of the objective function, the optimized sequence of energy storage output is obtained by using the intelligent algorithm to solve the mathematical model. In the earlier researches, only the function that can reflect the tracking performance is used to construct a single-objective optimization model. In [21], maximum similarity between the total output curve of

hybrid wind/photovoltaic/energy storage system and the given scheduled output curve is taken as the objective function. In [22], the matching degree is presented by the credibility value of effective tracking, and maximum the mean value of the total credibility value within a day is taken as the objective function. Single-objective-function-oriented control strategy is lack of consideration on economic use and prolonging service life of battery energy storage. Thus, some multi-objective-functions-oriented control strategies are proposed to improve the model. In [23], the tracking effect was measured by the Manhattan distance of the combined generation system output curve and the generation plan curve, and three objectives were used to simultaneously achieve the effective tracking of power generation plan, the smoothness of output, and insurance of sustainable work ability of battery energy storage. In general, the objective-function-oriented control strategy is with flexibility and extensibility since the objective function can be adjusted according to the practical control demands. However, objective-function-oriented control strategy is confronted with the problem of complex calculating, which is usually needs to be solved by intelligent algorithm.

Except for the four categories of control strategies mentioned above, some innovative researches can be found, which are thought-provoking for future studies. For instance, [24] comprehensively considered tracking inaccuracy together with battery energy storage level, energy loss, and put forward a variable charge/discharge time-interval control strategy. Literature [25] proposed a coordinated optimal control strategy, which consists of online rolling optimization and active power real-time control, to realize precise tracking.

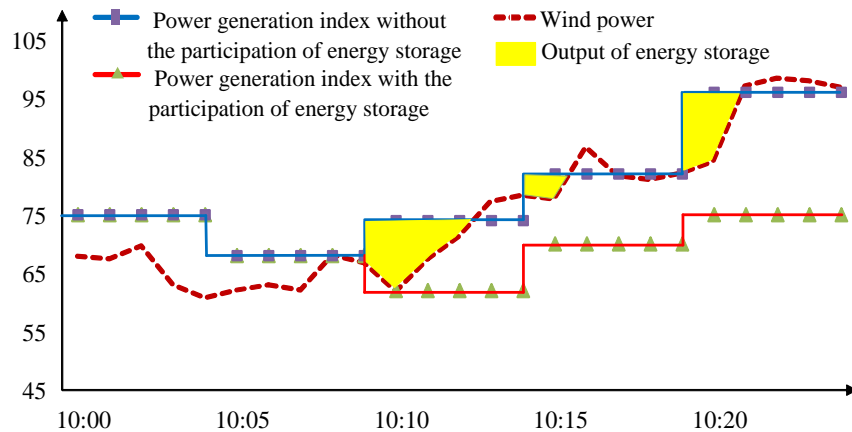
To sum up, traditional control strategies present basically satisfying performance for the wind power equipped with sufficient energy storage capacity. Otherwise, it is better to adopt forward-looking control strategies with overall management ability by considering the demand for energy storage strategy in certain period of future.

### *2.3. Tracking dynamic power generation index*

Dynamic power generation index is a concept proposed under the background of universal existence of wind power curtailment phenomenon in large-scale wind power centralized area of China, which is caused by transmission path constraint or power system peak regulation constraint. Taking the transmission path constraint as an example, which is mainly caused by the mismatch between the development of grid construction and increasingly installation demand for wind power generation, the dynamic regulation characteristic of power generation index can be referred to in literature [26] and [27].

Few literatures take the dynamic regulation characteristic of power generation index into concern, which might be explained by two reasons. One is that the curve of dynamic power generation index is harder to be obtained than a generation plan curve because the dynamic regulation characteristic of power generation index is related to the tracking performance of the wind farms in a certain period of the passed time. Even though simplify dynamic regulation characteristic of power generation index as a fixed amount of augment in the case that the wind farm tracked the index well in the past hour, and a fixed amount of curtailment in the opposite case, the possible target to track presents as a cluster of curves, the amount of which is up to  $2^{24}$ . It is unnecessary to take all the curves in the cluster as the tracking target and discussed one by one. Efforts might need to be made in how to select a reasonable number of curves from the curve cluster as the tracking targets to be studied. The other reason is that high demand on the control strategy of wind power and energy storage combined system is required with the dynamic regulation characteristic of power generation index being considered. As shown in figure 3, from 10:10 to 10:15, the participation of energy storage not only shortening the deviation between the power generation index and the wind power, but also contributes to obtain an augment of power generation index in the next control interval, which makes wind farm to be allowed to generate more power than that in the situation without energy storage. Thus, the overall management ability needs being attached more importance to when select the control strategy for tracking dynamic power generation index. The following ten minutes presents the similar situation.





**Figure 3.** Tracking dynamic power generation index with or without the participation of energy storage

Above all, future studies on tracking dynamic power generation index might be conducted from two perspectives, the modelling of dynamic power generation index and the control strategy fitting the scenario.

### 3. Multi-mode coordinated optimization and mode switching considering target tracking

Smoothing generation output, peak shaving and valley filling, control of target tracking, and frequency adjustment are the four modes of wind power and energy storage combined system. Majority of the literatures only concentrate on the coordinated control of the combined generation system on a single mode. For example, literatures mentioned in Section 2 only focus on the target tracking mode, and literature [28] studies the optimizations on different modes separately.

To furtherly exploit the energy storage capacity, in recent years, some researches have explored the multi-mode coordinated operation and switching of wind power and energy storage system. By surveying the relevant literatures, it is found that a few literatures on multi-mode coordinated optimization and mode-switching considering target tracking are available. Literature [29] proposed a multi-mode coordinated optimization model for the wind power and energy storage combined system and realized highly efficient utilization of limited energy storage on both the peak shaving mode and target tracking mode. Literature [30] explored the integrated operation and switching technology of energy storage system of photovoltaic power station stabilizing fluctuation, tracking the generation plan, and shifting the power peak, and these real-time control strategies, which is thought- provoking.

### 4. Conclusions

In order to realize the grid-friendly access of renewable energy power generation represented by wind power, it is necessary to involve energy storage, of which the battery energy storage is the most widely used type, and build a relatively controllable combined power generation system. Target tracking is one of the operation modes of the wind power and energy storage combined system, which is crucial to study. This paper reviews relevant literatures on target tracking of wind power and battery energy storage combined system. Here are the conclusions:

- According to the discrepancies in tracking target, the target tracking issue could be categorized into three parts, namely tracking wind power forecasting curve, tracking generation plan, tracking dynamic power generation index.
- Researches taking wind power forecasting curve as tracking target aims to use energy storage to make wind power forecasting error within the allowable deviation so as to meet the criteria of assessment and avoid punishment. According to the literature surveyed, with the assistance of energy storage, wind farm can basically meet the criteria of assessment.
- Researches taking generation plan as tracking target mainly concentrate on the improvement and innovation of control strategies, which can be categorized as tradition strategies and forward-looking strategies. Traditional control strategies present basically satisfying

performance for the wind power equipped with sufficient energy storage capacity. Otherwise, it is necessary to adopt forward-looking control strategies though they are relatively complex.

- Dynamic power generation index is proposed for the full and fair utilization of the wind power in the large-scale wind power centralized areas with transmission path constraint problem. Few literatures on dynamic power generation index tracking are found, which may be explained by two reasons. One is the difficulty in obtaining the curve of dynamic power generation index. Another is high demand on the overall management ability of control strategy.
- Researches on multi-mode coordinated optimization considering target tracking and mode switching for wind power and energy storage combined generation system is still at a preliminary stage.

The improvement and innovation of control strategies in tracking generation plan still need further studies. More importantly, the issue of tracking dynamic power generation index and that of multi-mode coordinated optimization are worth exploring and should be paid more attention to in future work to furtherly make a full play of energy storage and promote the development of wind power.

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