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Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.
Digital Object Identifier 10.1109/ACCESS.2017.Doi Number

A new definition method of wind power ramp sections

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This work was supported by Hunan Natural Science Foundation under Grant 2018JJ4076.
This work was supported by Hubei Key Laboratory Open Foundation under Grant 2019KJX06.

ABSTRACT A new definition method of ramp sections is proposed. Firstly, the extreme point extraction algorithm is designed. The results show that the extreme value sequence can not only achieve data compression, but also provide data for the definition of the ramp section. Secondly, several typical recognition methods of wind power ramp are compared. The results show that the "event" as the unit of analysis is not possible to effectively distinguish between the ramp process and the transient process in the ramp event, which causes the prediction error of the ramp duration. Also, the non-representation of the threshold setting will also cause errors in the prediction and recognition of complex ramp events. In this paper, the concepts of ramp section, slope point(SP) and stagnation point(STP) are introduced to realize the segmentation processing and analysis of ramp events, which can effectively distinguish the ramp process and transient process in ramp events and provide a strong guarantee for the accurate prediction of the ramp duration. In addition, the mathematical statistics method of cumulative probability is utilized to discuss the threshold setting. The ramp situation of a wind farm in Yunnan in 2014 is further identified and analyzed, and on this basis, the characteristics of the ramp sections are investigated, whose results show the applicability of this new definition.

INDEX TERMS Wind power ramp sections, definition method, extreme point extraction, applicability

I. INTRODUCTION

The essence of wind power generation is to convert wind energy into electric energy. The random fluctuation of wind determines that the output power of wind power generation is also volatile. In serious cases, it can result in radical changes in wind power in a short period of time, that is, wind power ramp events. These events have potential threats to the stable operation of the power grid, and could seriously affect the safety and stability of the power grid [1]. Many countries have seen the occurrence of these similar events [2-3]. In order to deal with these challenges, it is necessary to study the basic characteristics of wind power ramp events, and the definition of wind power ramp events is the basis of analyzing these events.

In recent years, the definition of wind power ramp events are not highly appreciated. Instead, the prediction of wind power ramp events is the hot SPot, in which the probability prediction is the focus. However, the definition and identification of wind power ramp events is the basis of the prediction. Under the same prediction methods, different definition methods will cause different prediction errors, resulting in different prediction results under different definition frameworks. James et al. recognize a ramp event when the power jump quantity exceeds a certain threshold at a certain time period, then predict its probability, and experiment on the prediction results under different thresholds, whose experimental results change with the threshold value [4]. In [5], a generalized Gaussian mixture model is developed to describe the wind power forecasting errors generated from a machine learning technique, and generate quantity of forecasting errors scenarios. The OpSDA is applied to conduct the probabilistic wind power ramp forecasting based on the generated scenarios under different weather and time conditions. By considering the stochastic correlation of different wind ramp features (magnitude, rate, start-time and duration), [6] investigates a conditional probabilistic wind power ramp forecasting model based on Copula theory. The Gaussian mixture model (GMM) and Bayesian information criterion are applied to fit and choose the optimal copula model for improved accuracy in prediction.

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However, its essence is to extract and predicate the ramp characteristics of historical data, which is still within the limitation of ramp definition [6].

There is no unified and recognized definition for wind power ramp events among the existing research results. Cutler, Greaves, Grimit et al. propose that in order to define, describe and identify ramp events, it is necessary to determine the direction, rate and height of ramp events [7], [8], [9].

Truewind (2008) gives the first definition of a ramp event, that is, if the amplitude of the output power of a wind farm has a large enough change in a short period of time, it can be called a wind power ramp event. Truewind thinks that the condition of the uphill event is that the output power of the wind farm changes by at least 20% of the installed capacity of the wind farm within one hour, and the condition of the downhill event is that the variation range of the output power of the wind farm is at least 15% of the installed capacity of the wind farm within one hour [10].

Greaves (2009) proposes more stringent ramp event conditions. He believes that only when the amplitude of wind farm output power changes by at least 50% within about 4 h, can a wind power ramp event be recognized in the wind farm [8].

Zheng et al. (2009) use wind power data of 100 wind farms with installed capacity of 133.5mw of every 10 min from January 1 to January 31, 2007, and propose a ramp event definition with ramp rate as the threshold parameter. The concept of ramp rate is the change rate of wind power relative to the ramp interval [11]. Cui et al. believe that this definition is more complete. The ramp event is identified by the increase or decrease speed of wind power, and the recognition rate is improved [12]. However, the drawback of this definition is that it is difficult to select the time interval when calculating the ramp rate. Zheng et al. propose the definition by using the time interval of every 10 min in 10-60 min to identify the ramp event. It is found that the recognition accuracy is higher when the time interval is 10 - 40 min, and it is lower when the interval is 50 - 60 min. Besides, it is pointed out that if the meteorological data is used in the identification of ramp events, the recognition rate of 1 -3 h in time interval is higher. Therefore, when adopting this definition, a lot of research work has to be done in the selection of time interval, which is cumbersome. In addition, Cameron et al. give suggestions on the threshold value of upward and downward ramps in this definition: for upward ramps, if the power change exceeds 20% of the total installed capacity, an obvious ramp event occurs; while for downward ramps, the threshold is 15% of the total installed capacity [7]. Based on the wind power data of Tehachabi wind farm in Southern California from 2007 to 2008 and the data of the wind farm in northern Oregon from 2007 to 2009, Kamath et al. (2010) study and analyze the height and duration of ramp events, and give the mathematical definitions of three kinds of ramp events [13], [14]. The first definition is given by comparing whether the difference between the power value at the beginning of the later time interval and that at the end of the previous time interval is greater than the threshold value. It is relatively simple and convenient in practice. It is the mainstream definition of ramp events in the world. However, only the wind power value at the end of the ramp interval is considered, while the power variation characteristics in the middle of the ramp interval are ignored, therefore it has some limitations. The second definition is decided by comparing whether the time range exceeds the threshold. Compared with the first definition, the amplitude of all wind power fluctuations in the interval ΔT is considered, by which the ramp events can be identified more accurately in practice, but there are also some shortcomings. It ignores the change rate of wind power, which results in certain errors in practice, and it can not directly identify the ramp direction. The third definition is developed by judging whether the average variation of wind power in a given period of time exceeds the threshold value. This definition has one disadvantage. When there are both upward and downward ramp ranges in the selected time interval, the positive and negative values can cancel each other in the calculation of ΔP, resulting in the failure to identify the ramp events.

Bossavy et al. (2010) introduce a variable related to both time and wind power, and give a definition slightly different from the original definition of ramp events. The definitions described above are for direct calculation of wind power sequence, while he first makes K-order difference for wind power amplitude to get a signal sequence more suitable for judging ramp events, and then uses the converted signal sequence to define ramp events. The advantage of this definition is that the starting and ending time of ramp process can be determined by using the maximum point of time step sequence, and the ramp direction can be determined based on the corresponding wind power value of the maximum point, but more experiments are needed to verify this definition applicability to the ramp events [15].

In recent years, no new definition of ramp events has been studied. According to the above ramp definitions, wind power ramp events that may occur in wind power data can be identified [16], but there are some defects: (1) for the same wind farm station and the wind power sequence of the same time period, when the above definitions are separately adopted to identify ramp events, the identification and extraction results are different, which has many inconveniences in practice. (2) Although the existing definitions of ramp events can denote the uphill and downhill segments of a ramp event, there is often a transition process between the uphill segment and the downhill segment, that is, the power gentle segment in the ramp event. Therefore, the event-based analysis model can not clearly distinguish the ramp sections from the gentle section in the ramp event, which often leads to the statistical error of the ramp duration. (3) The existing definitions of ramp events do not specify a minimum power change amplitude, nor a maximum time interval. In this case, the power amplitude in a certain period of time exceeding the threshold cannot be used as a criterion for determining a ramp event. Currently, there is

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no unified definition which has integrated the advantages of the above definitions and can be concise, convenient and credible in practice. Therefore, it is necessary to analyze and study the ramp events and the existing identification methods of ramp events to determine a more reasonable identification method of ramp events.

Aiming at the problems faced by the definition of ramp events, this paper establishes a general definition model of wind power ramp events, so as to provide a unified definition reference for future wind power ramp event identification and prediction. Therefore, this paper mainly makes the following contributions: (1) An extreme value extraction algorithm is designed. A set of general ramp event analysis data can be obtained by extracting the power extreme values from the original power sequence. The obtained power extreme value sequence has retained the original information as much as possible. Besides, it also serves as the data basis for the definition of ramp sections. The change amplitude, change speed and duration of power extreme values are counted to provide reference for the setting of ramp threshold. (2) A definition model of ramp section is established. By defining uphill point(UP), STP and downhill point(DP), the ramp event can be segmented into ramp sections, which can effectively distinguish power ramp area from power gentle area. Both ramp amplitude and ramp rate are limited in order to reduce the influence of power fluctuation. (3) The ramp threshold is set. The empirical method has been adopted to set most of the ramp thresholds, while in this paper, firstly, the change amplitude, change speed and duration of power extreme values are counted, and then their cumulative probability distribution is analyzed, and the ramp threshold is set by their corresponding cumulative probability thresholds. (4) With the identification method of wind power ramp section based on extreme value extraction algorithm, and the specific wind farm data, the ramp sections are identified, and the characteristics of ramp range, ramp rate and duration are analyzed.

The rest of this paper is organized as follows: Section 2 clarifies the overall architecture. Section 3 introduces the extreme value extraction algorithm, which provides data support for the later research on the definition of ramp segment. Section 4 investigates the definition process of ramp segment and the discussion process of both thresholds of ramp segment. Section 5 analyzes the applicability of the proposed method with specific cases. Finally, the conclusions are drawn in Section 6.

II. Basic ideas

The ramp event refers to a large-amplitude wind power change within a short period of time. Therefore, ramp amplitude and ramp rate can be adopted to redefine the wind power ramp events. The selection of the ramp threshold is the key to the ramp identification. In theory, the smaller the threshold, the more likely it is to cover all possible ramp events, but it is difficult to eliminate the influence of small power fluctuations, and it would add some redundant information and affect the recognition accuracy. On the omitted. In addition, what the ramp rate reflects is the change process of the ramp event, and if the rate is too low, it cannot be the prerequisite for a ramp event.

Statistical analysis of data at different sampling time points is performed as one of traditional definition methods to identify the ramp events. In this case, the data at different sampling times has different ramp events defined. This paper first looks for the extreme points of historical wind power sequence, then analyzes and identifies ramp events based on this sequence, to avoid the difference in ramp identification under different definition standards.

At present, the wind power ramp is generally studied by the event, and a complete ramp event is composed of several ramp sections. Therefore, this paper takes ramp sections as the study object, and proposes a new identification method of ramp sections. The basic idea is shown in Fig. 1.

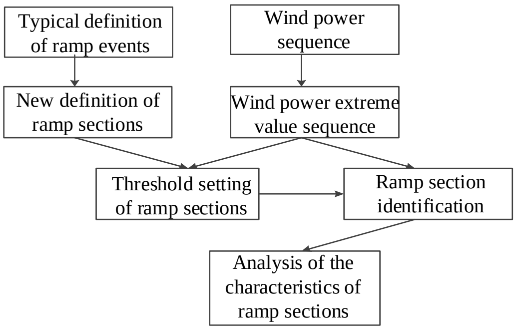

FIGURE 1. **Basic flow of ramp event recognition.**

As shown in Fig. 1, on the one hand, the extreme point extraction is performed on the original wind power sequence to get the extreme value sequence. On the other hand, the new definition comes from the typical definitions of the ramp events. Then based on the above two aspects, the thresholds of ramp amplitude and ramp rate are set to identify the ramp sections. Finally, the characteristics of the ramp sections identified in a specific area are analyzed.

III. Extreme point extraction process

The extreme point extraction method extracts the extreme value of the original sequence by searching for local extreme points, so as to obtain the ramp characteristics. Assuming the original data matrix is X, then X can be expressed as follows:

$$\begin{cases} X = \begin{bmatrix} T_1, T_2, ..., T_i, ..., T_m \\ P_1, P_2, ..., P_i, ..., p_m \end{bmatrix}^{\mathrm{T}} \\ i = 1, ..., m \end{cases} \tag{1}$$

where X is the original data matrix, T is the original time, P is the original power, and i is the original data volume. The specific process of extracting extreme sequence from X is as follows:

Step 1: Initialize the beginning and end of E to the beginning and end of X:

$$\begin{cases} E(1,1) = T_1; E(1,2) = P_1 \\ E(d,1) = T_m; E(d,2) = P_m \end{cases} \tag{2}$$

where E is the extreme value matrix and d is the number

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of extreme points.

Step 2: Judge the given condition of Eq. (3):

$$\begin{cases} 1: P_{i-1} > P_i < P_{i+1} \\ 2: P_{i-1} < P_i > P_{i+1} \end{cases} \tag{3}$$

When the condition 1 is satisfied, it is the minimum point. When the condition 2 is satisfied, it is the maximum point. T_i and P_i at the extreme points are stored then in E.

Step 3: Correct the beginning value of the extreme value matrix:

$$S_{\text{begin}} = \frac{E(2,2)-E(3,2)}{E(2,1)-E(3,1)} \tag{4}$$

$$L_{\text{begin}} = S_{\text{begin}}(E(1,1)-E(2,1))+E(2,2) \tag{5}$$

where S_{begin} is the beginning slope, and L_{begin} denotes the beginning correction value. Eq. (4) and Eq. (5) are used to correct the beginning value of E.

Step 4: Correct the end value of the extreme value matrix:

$$S_{\text{end}} = \frac{E(d-1,2)-E(d-2,2)}{E(d-1,1)-E(d-2,1)} \tag{6}$$

$$L_{\text{end}} = S_{\text{end}}(E(d,1)-E(d-1,1))+E(d-1,2) \tag{7}$$

where S_{end} is the end slope, and L_{end} denotes the end correction value. Eq. (6) and Eq. (7) are used to correct the end value of E.

The rationale and implementation process of the extreme point extraction method are described in the preceding four steps. The wind power data in a 50MW wind farm is measured every 15 min, and in this way the effectiveness of the extreme point extraction method is verified as shown in Fig. 2.

In Fig. 2, the solid blue line represents the extraction feature of extreme points, and + is the actual power point. It can be seen from this figure that the extreme point extraction method can effectively extract the extreme points in the power sequence, and use limited extreme data to present the change of the original sequence, so as to compress the data and extract the features.

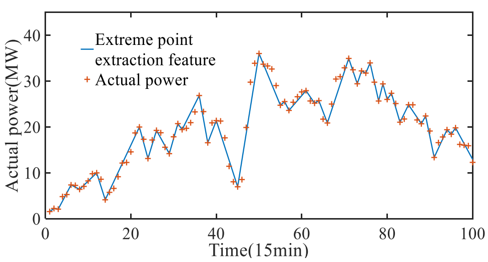

FIGURE 2. **Comparison of extreme point extraction results.**

In order to do the following analysis, the extreme point is called the temporary ramp point (TSP), and the extreme value sequence E is called temporary ramp point sequence Y, that is,

$$\begin{cases} Y = \begin{bmatrix} T_1^{\text{Y}}, & T_2^{\text{Y}},\ldots,T_j^{\text{Y}},\ldots,T_n^{\text{Y}} \\ P_1^{\text{Y}}, & P_2^{\text{Y}},\ldots,P_j^{\text{Y}},\ldots,P_n^{\text{Y}} \end{bmatrix}^{\text{T}} \\ j = 1,..,n \end{cases} \tag{8}$$

where Y is the TSP matrix, T^{Y} and P^{Y} are the time and power of TSP respectively, and j denotes the number of TSPs.

IV. Definition of ramp sections and threshold setting

A. Definition of ramp sections

1) TYPICAL DEFINITIONS OF A RAMP EVENT

The definition of a ramp event is the prerequisite for its recognition. However, there is no unified definition formed in the industry. Several typical ramp event definitions are summarized.

Definition 1: Set a time interval $[t, t + \Delta T]$, when the difference of the power value between the cutoff time and the start time in this time interval is greater than a certain threshold λ in Eq. (9), it is considered that a power ramp event occurs during this time interval, where $P(\text{t})$ denotes the power value at t and λ represents the ramp amplitude threshold.

$$|P(t+\Delta T)-P(t)| > \lambda \tag{9}$$

When the amplitude change is more than 15-20% of the total installation capacity, it is recognized as a ramp event [12]. The result shows that the amplitude threshold λ of the experimental wind farm is about 7.5-10 MW, and the average is 8.75 MW. Fig. 3 is the ramp recognition diagram drawn from Definition 1 when Eq. (9) is taken and λ is 8.75 MW.

As can be seen from Fig. 3, Definition 1 can identify a simple ramp event in the power sequence. But it only considers λ, and does not take into account the ramp rate, that is, the power change during the ramp process, which may result in loss of power characteristics. In addition, setting the threshold only based on the wind farm capacity is not effective enough to reflect the actual power amplitude change of the wind farm, which may cause some identification omission.

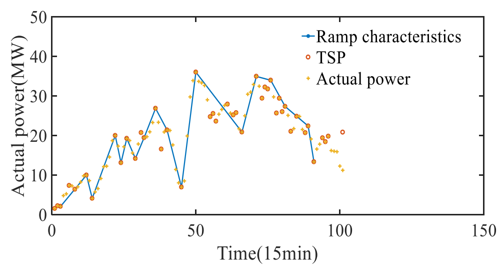

FIGURE 3. **Ramp diagram from Definition 1.**

Definition 2: First define a certain time interval $[t, t+\Delta T]$, then find the maximum and the minimum value in this time interval, and take its range. When the range is greater than the threshold λ which is formulated as follows, it can be considered as a power ramp event during this time interval.

$$\max(P[t,t+\Delta T])-\min(P[t,t+\Delta T]) > \lambda \tag{10}$$

This definition thinks of the power amplitude over the time interval, but it does not consider the change rate during this time period.

Definition 3: Define a time interval $[t,\ t+\Delta T]$, and calculate the power rate in this time period. When the power change rate is greater than the threshold β in Eq. (11), then a power ramp event occurs during this time interval.

$$\frac{|P(t+\Delta T)-P(t)|}{\Delta T} > \beta \tag{11}$$

In Eq. (11), β is the ramp rate threshold. At the same time, this definition can distinguish the uphill and downhill events. When $P(t) < P(t+\Delta T)$, Eq. (11) defines an uphill event, while when $P(t) > P(t+\Delta T)$, it is regarded as a downhill event.

Only when the wind farm power changes more than 50% of the installation capacity within 4 h, can a ramp event be recognized. Therefore, the corresponding ramp rate threshold β can be calculated to be 0.1 MW/min [8]. Combined with Eq. (11), the ramp chart identified by Definition 3 can be obtained, as shown in Fig. 4.

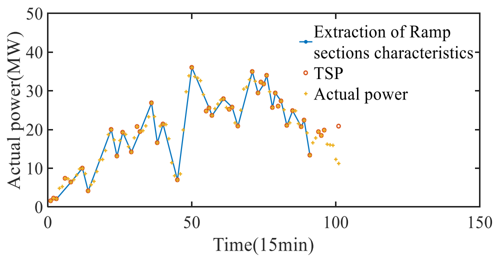

FIGURE 4. **Ramp diagram from Definition 3.**

It can be seen from Fig. 4 that although the power change can be accurately characterized by the ramp rate, the points with small change amplitude are extracted as well. In this case, the ramp events can not be clearly identified and it increases the redundancy of ramp events.

The above definition methods can identify the possible ramp events in the wind power, but each has its own shortcomings. For the same power sequence, the above definitions have different identification results and can not be popularized in practice as a consequence. In addition, for the complex and long-term ramp events, there are non-ramp intervals and fake ramps caused by human factors, which results in the misrecognition of ramp events. In the following, the section method is adopted, and on the basis of typical ramp definitions, the ramp sections are defined, and the setting method of the ramp threshold is discussed and investigated.

2) NEW DEFINITION OF RAMP SECTIONS

It can be seen from Fig. 3-4 that it is difficult to identify the complicated ramp events simply by using the Definitions 1-3. In this paper, the ramp event is segmented, and the Definitions 1-3 are combined and optimized. Combined with Y extracted from the equations (1)-(7), the ramp sections are redefined, as shown in Eq. (12) .

$$\begin{cases} \text{slope point:} \left|P_{j+1}^{\mathrm{Y}}-P_{j}^{\mathrm{Y}}\right| > \lambda (\text{condition 1})\ \delta\delta\ \beta_{\max} > \dfrac{\left|P_{j+1}^{\mathrm{Y}}-P_{j}^{\mathrm{Y}}\right|}{T_{j+1}^{\mathrm{Y}}-T_{j}^{\mathrm{Y}}} > \beta (\text{condition 2}) \\ \text{stationary point:} \left|P_{j+1}^{\mathrm{Y}}-P_{j}^{\mathrm{Y}}\right| < \lambda\ \|\ \dfrac{\left|P_{j+1}^{\mathrm{Y}}-P_{j}^{\mathrm{Y}}\right|}{T_{j+1}^{\mathrm{Y}}-T_{j}^{\mathrm{Y}}} < \beta \end{cases} \tag{12}$$

In Eq. (12), βmax is the maximum power change rate of the network, which is determined by the wind farm capacity and the power grid, see the specific reference values in Table 1.

TABLE I
RECOMMENDED VALUE OF MAXIMUM POWER RATE CHANGE OF WIND FARM

Capacity (MW)	Maximum change in 10 mins (MW)	Maximum change in 1 min (MW)
< 30	20	6
30 - 150	Capacity / 1.5	Capacity / 5
> 150	100	30

In Eq. (12), the ramp amplitude and the ramp rate are limited. First, the power amplitude change between TSPs is decided, that is, condition 1. When this condition is satisfied, the power change rate between TSPs is examined, that is, condition 2. When two conditions are both satisfied, it is considered that a ramp event has occurred between TSPs, and point j is deemed a ramp point (SP), and the ramp point matrix Z is formulated as follows:

$$\begin{cases} Z = \begin{bmatrix} T_1^{\mathrm{Z}}, & T_2^{\mathrm{Z}}, ..., T_q^{\mathrm{Z}}, ..., T_r^{\mathrm{Z}} \\ P_1^{\mathrm{Z}}, & P_2^{\mathrm{Z}}, ..., P_q^{\mathrm{Z}}, ..., P_r^{\mathrm{Z}} \end{bmatrix}^{\mathrm{T}} \\ q = 1, .., r-1 \end{cases} \tag{13}$$

In Eq. (13), Z is SP matrix, T^{Z} and P^{Z} are the time and power of SP respectively, and q is the number of SPs.

The combination of these two conditions can better reduce the information redundancy of complex ramp sections. Since T^{Y}_{j}-T^{Y}_{j-1} is not a fixed time interval, λ and β do not constitute a fixed mathematical relationship, instead, they are two independent conditional thresholds. The setting of λ and β is discussed below.

The concept of the stationary point (STP) is introduced in Eq. (12), in which the TSP with ramp amplitude smaller than λ or ramp rate less than β is defined as the STP. The continuous STP can be replaced by a horizontal line, whose value is equal to that of the first STP, that is, FSP. By introducing STP, it can effectively distinguish and identify the power ramp period and the gentle zone, clearly count the ramp events cycle, and minimize the redundancy of ramp sections and the statistical error of ramp duration.

B. Discussion of ramp threshold setting

1) SETTING OF β

Condition 2 of Eq. (12) has defined the calculation method of ramp rate. The rate of adjacent TSPs are calculated and presented in Fig. 5a in terms of its cumulative probability distribution and confidence interval. In Fig. 5a, it shows that more than 90% of the ramp rate is less than $\beta_{\max}$, indicating that most of the ramp rate can meet the power grid

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connection requirements, and over 80% of the rate is greater than 0.98 MW/min. According to the recommendation given in the literature [12], the ramp rate threshold of this wind farm can be determined to be 0.1 MW/min, which indirectly verifies that it is effective to use the mathematical statistics method for setting the ramp threshold. From Eq. (12), when the power change rate of a certain time interval is greater than a certain threshold value, a ramp event may occur in that period. According to the mathematical statistics of Fig. 5a, when the absolute value of the power change rate is greater than or equal to 0.98MW/min, more than 80% of the power changes are included, and it conforms to the current mainstream views on the threshold setting of ramp rate.

2) SETTING OF λ

As shown in Fig. 3, the ramp amplitude can be determined by the installation capacity. Although it can identify large ramp sections, it is insensitive to the small sections, and fails to distinguish the power stabilization period and the ramp period effectively, which may cause some statistical errors of ramp duration. The reason is that it does not consider the actual power change of the wind farm when setting the λ. If the ramp amplitude threshold is set too high, it can not effectively reflect the internal change characteristics of the actual power sequence.

In view of the above problems, this paper uses mathematical statistics to calculate the ramp amplitude change among the TSP sequences and its cumulative probability, so as to determine the ramp amplitude threshold, as shown in Fig. 5b. It can be seen that over 80% of the amplitude changes is less than 8.31 MW, over 60% is less than 5.28 MW, over 40% is less than 3.59 MW, and more than 20% is less than 1.3 MW. By selecting different amplitude change probability intervals, different thresholds of ramp amplitude are set, and the optimal threshold is selected according to the actual power change of the wind farm.

Fig.s 5c-5f show the ramp identification diagrams when β equals 0.98 MW/min, and λ equals 29.06 MW, 8.31 MW, 5.28 MW, 3.59 MW, 1.3MW, 0.15MW respectively. As the charts show, different ramp amplitude can identify different ramp processes. The lower amplitude threshold can describe the ramp process well, but it can not avoid the small power fluctuations, and may have some identification errors. As the threshold goes high, the fluctuations can be eliminated, and the ramp process can be characterized with fewer points.

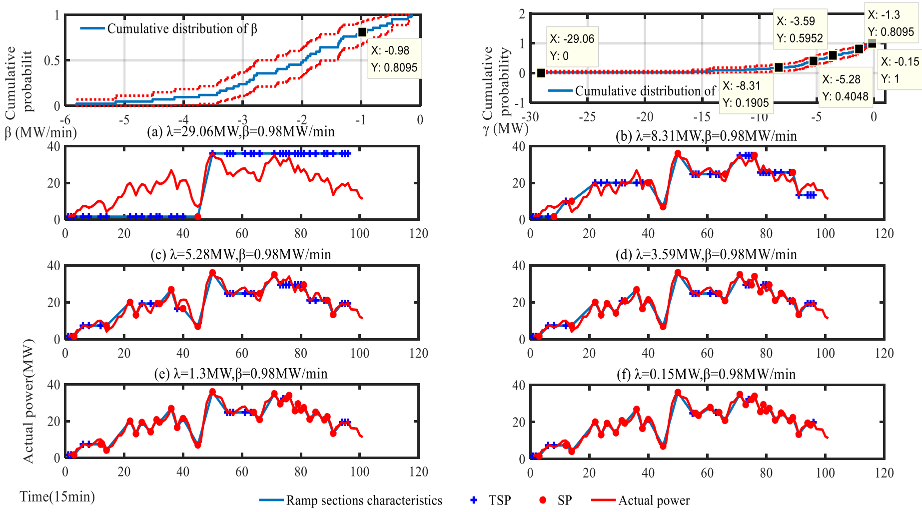

FIGURE 5. Ramp diagrams under different ramp amplitude thresholds.

Compared with the traditional methods, mathematical statistics can set the ramp amplitude thresholds more flexibly. By statistically analyzing the historical data of a specific wind field and summarizing the amplitude changes of historical power, the threshold of ramp amplitude is flexibly set, and the ramp event is identified accordingly. The relationship among ramp amplitude, ramp rate and wind power prediction is analyzed. The result shows that there is a certain functional relationship between ramp characteristics and prediction error, and as the ramp amplitude and ramp rate increase, the power prediction accuracy tend to decline [17]. This finding paves the way for the precise setting of ramp threshold. How to properly select the ramp threshold to minimize the error of wind power prediction is one of the future research directions.

V. ramp section recognition based on extreme point extraction

By redefining the ramp sections and discussing the ramp threshold, together with the threshold selection experience in the typical ramp definitions, when λ is set to 8.31 MW and β is 0.98 MW/min, if the ramp rate is greater than or equal to β, it is identified as an uphill point (UP), while if the ramp rate is less than $-\beta$, it is identified as a downhill point (DP), and the identified ramp characteristics are shown in Fig. 6. Based on this, the ramp duration is counted and shown in Fig. 7. The identification of uphill and downhill ramp points is formulated as shown in Eq. (14), and the ramp duration is

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formulated as shown in Eq. (15).

$$\begin{cases} \mathrm{UP}: \dfrac{P_{q+1}^{Z} - P_{q}^{Z}}{T_{q+1}^{Z} - T_{q}^{Z}} > \beta \\ \mathrm{DP}: \dfrac{P_{q+1}^{Z} - P_{q}^{Z}}{T_{q+1}^{Z} - T_{q}^{Z}} < -\beta \end{cases} \tag{14}$$

$$T = \begin{cases} T_{q+1}^{Z} - T_{q+1}^{Z} \\ T_{\mathrm{FSP}} - T_{q+1}^{Z} \end{cases} \tag{15}$$

In Eq. (15), T_{FSP} is the time for FSP.

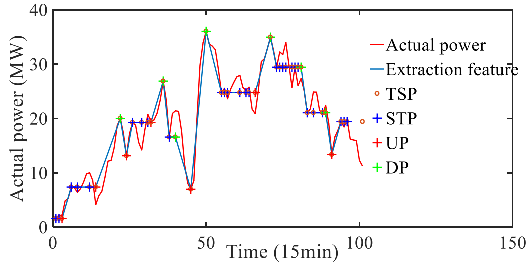

FIGURE 6. Wind power ramp diagram based on extreme point extraction.

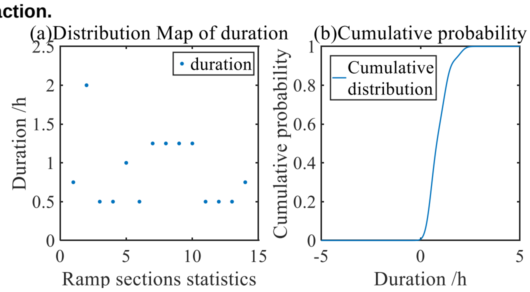

FIGURE 7. Ramp duration diagram.

Fig. 7a shows the distribution of ramp duration. A total of 14 ramp sections are identified, of which the shortest ramp duration is 0.5 h, the longest is 2 h, and the average is 0.9 h. Fig. 7b is charted as the cumulative distribution of ramp duration, which shows that over 90% of the ramp duration is within 1.543 h.

In order to identify the ramp sections based on the extreme point extraction, combined with the previous analysis, the basic flow of the algorithm is elaborated as follows:

Step 1: According to the extreme point extraction method and the equations (1)-(7), the extreme point extraction is performed on the historical actual power sequence to obtain the extreme sequence E, and this sequence is also called the temporary ramp point sequence Y.

Step 2: According to the condition 1 of Eq.(12) and the TSP sequence, the power amplitude change is calculated, whose cumulative probability distribution is further analyzed to set λ .

Step 3: According to the condition 2 of Eq.(12) and the TSP sequence, the power change rate is calculated, whose cumulative probability distribution is further analyzed to set β.

Step 4: According to the parameters determined in Step 2 and Step 3, SP can be identified from the SP recognition conditions in Eq. (12), the UP and DP can be identified from Eq. (14), and the ramp duration obtained from Eq. (15).

VI. Identification and Characteristics Analysis of Wind Power ramp Events in Yunnan Province

By using the above algorithm, the actual wind power data of a 50 MW wind farm base in Yunnan in 2014 is identified and statistically analyzed every 15 minutes. Ramp amplitude, ramp rate and ramp duration are three main dimensions involved. On this basis, the empirical distribution of ramp amplitude, the joint distribution of ramp rate and duration, and the joint distribution of ramp amplitude and duration are analyzed to explore the practicability of ramp definition and identification based on extreme point extraction method in the wind farm.

A. Analysis of ramp amplitude

The ramp amplitude distribution of ramp sections of the wind farm obtained from the extreme point extraction method is shown in Fig. 8, where the CAP denotes the farm installation capacity. From Fig. 8, it can be seen that ramp sections with the ramp amplitude at 20-30% CAP has the largest proportion about 50.09% of the total. The ramp amplitude at 30-40% CAP account for 22.17% of the total. The ramp sections with the ramp amplitude at 40-50% CAP and 50-60% CAP make up 14.6% and 6.57% respectively. The ramp amplitude at 60-70% CAP, 70-80% CAP and 80-90% CAP account for 2.92%, 2.92% and 0.73% of the total, with the proportion less than 5%.

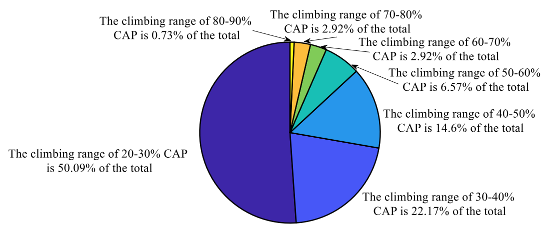

FIGURE. 8. Ratio of ramp times in different amplitude ranges to the total ramp times.

Fig. 9 shows the frequency and empirical distribution of ramp events of the wind farm. The analysis indicates that it accords with the empirical distribution of the wind field ramp amplitude under normal conditions. When the ramp amplitude is less than 4.6 MW, the ramp frequency tends to increase, reaching a peak at around 7 MW. When the ramp amplitude exceeds 4.6 MW, the frequency gradually decreases, and when the ramp amplitude is over 40 MW, the frequency reaches a plateau at 0, basically no ramps with the ramp amplitude higher than 40 MW. According to the data, the average ramp amplitude of ramp sections identified by the extreme point extraction method is 10.3488 MW, indicating that most of ramp sections are concentrated near the average ramp amplitude. In combination with Fig. 8, it can be found that most of ramp sections of this wind farm are concentrated between 20% and 50% CAP (5-25 MW), which is a small-amplitude ramp, and the probability to have large-

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2020.3032547, IEEE Access

amplitude ramp is relatively low. This kind of ramp characteristics are related to the meteorological environment: the environment around this wind farm is relatively stable.

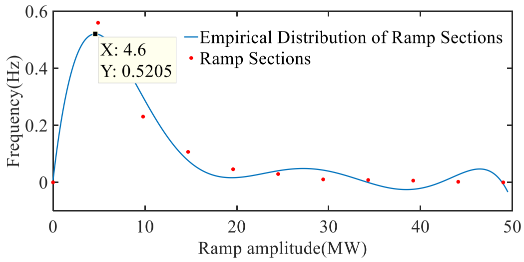

FIGURE 9. Frequency and empirical distribution of ramp amplitude.

B. Joint distribution of ramp rate and duration

Fig. 10 shows the joint distribution of ramp rate and ramp duration. It can be seen that most of the ramp sections last less than 1 h with the ramp rate about 10-40 MW/h. The ramp rate of the contour center is 8.267 MW/h and the duration of about 0.55 h. The ramp rate and the duration are in an inversely proportional relationship.

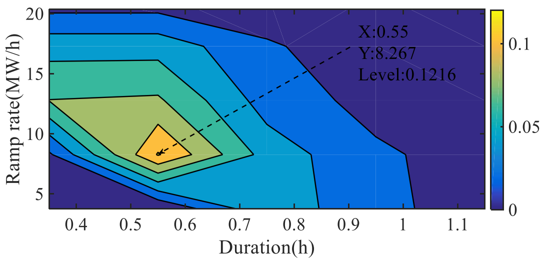

FIGURE 10. Joint distribution map of ramp rate and ramp duration (contours indicate the sample frequency correSPonding to horizontal and vertical values).

C. Joint distribution of ramp amplitude and duration

Fig. 11 is a joint distribution diagram of ramp amplitude and duration of the wind farm. From this figure, most of the ramp sections are in the ramp amplitude of 4-20 MW and the ramp duration of 0.5-1.5 h. The ramp amplitude of the contour center is near 5.733 MW and the ramp duration of around 0.35 h.

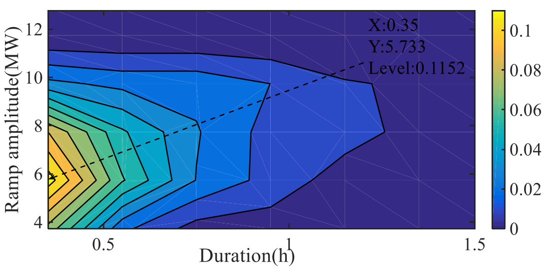

FIGURE 11. Joint distribution of ramp amplitude and duration (contours indicate the sample frequency correSPonding to horizontal and vertical values).

Based on the analysis of ramp amplitude, ramp rate and ramp duration, the ramp sections identified by this method has the following characteristics: most of the ramp sections have the ramp amplitude less than 50% CAP, which belong to the small and medium ramps, and the frequency of large-amplitude ramps is relatively low. As the ramp duration increases, the ramp rate tends to decrease. By analyzing the characteristics of ramp sections of the wind farm, the accuracy of wind power prediction can be improved, and this could provide a reliable scientific reference for grid dispatching.

VII. Conclusion and Outlook

This paper proposes a wind power ramp section recognition method based on extreme point extraction. Through experiments and simulations, the following conclusions are drawn:

1) The existing typical ramp identification methods have some limitations: Definition 1 is insensitive to small-amplitude ramps, and the identified ramp events can not effectively reflect the actual power characteristics. Definition 2 does not consider the change rate characteristics in a time interval while Definition 3 fails to eliminate the interference of small power fluctuations.
2) The extreme point extraction method designed in this paper can effectively extract the extreme points of the original sequence and achieve data compression. The ramp threshold set by mathematical statistics method can reflect the actual power trend. By introducing the STP, the ramp and non-ramp processes can be distinguished more clearly, and the calculation of ramp duration can be facilitated. The ramp section identification method based on extreme point extraction can effectively identify the ramp process in the power sequence. It is worth noting that this method is based on statistics, so the data statistics and analysis is crucial. In practice, more data needs to be included and analyzed to test it.
3) By analyzing the characteristics of ramp amplitude, ramp rate and ramp duration of ramp sections of a wind farm in Yunnan, it is demonstrated that the characteristics of each extracted ramp section are reasonably distributed, which indicates that the ramp section identification method based on extreme point extraction is applicable. The future research could aim at the identification and statistical analysis of historical ramp sections, and the correction of future power predictions.

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