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Convex decomposition of concave clouds for the ultra-short-term power prediction of distributed photovoltaic system①

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Abstract

Concave clouds will cause miscalculation by the power prediction model based on cloud features for distributed photovoltaic (PV) plant. The algorithm for decomposing concave cloud into convex images is proposed. Adopting minimum polygonal approximation (MPP) to demonstrate the contour of concave cloud, cloud features are described and the subdivision lines of convex decomposition for the concave clouds are determined by the centroid point scattering model and centroid angle function, which realizes the convex decomposition of concave cloud. The result of MATLAB simulation indicates that the proposed algorithm can accurately detect cloud contour corners and recognize the concave points. The proposed decomposition algorithm has advantages of less time complexity and decomposition part numbers compared to traditional algorithms. So the established model can make the convex decomposition of complex concave clouds completely and quickly, which is available for the existing prediction algorithm for the ultra-short-term power output of distributed PV system based on the cloud features.

Key words: distributed photovoltaic (PV) system, cloud features model, centroid point scattering model, convex decomposition

0 Introduction

The power output of a photovoltaic (PV) system mainly depends on the sun radiation received by the PV panels when the photoelectric conversion efficiency for the PV models is stable. The sun radiation received by the PV system will be decreased because of the cloud shielding. The cumulus in the 3km sky can shelter 72% of sun radiation[1]. The sun radiation sheltered by the random moving cloud will result in a distributed PV system power output fluctuation[2]. The recent research on power prediction for PV system mainly focuses on short-term prediction at a scale of 24 hours[3]. The distributed PV systems were usually deployed in the user side, which is smaller than PV plant in size and power generation. They are easy to be affected by the moving cloud clusters because of the fluctuation of the received sun radiation resulting from cloud shielding, which often happens in the second time scale[4]. The timescale of short-term prediction is still relatively too large to predict the distributed PV system power output fluctuation, which is so sharp that it may influence or even damage sensitive electrical devices. The prediction of distributed PV power output fluctuation will be realized by real-time monitoring and analysis on dynamic characteristics of clouds, which aims to estimate the shielding effect to the sun radiation[5]. The model of cloud prediction based on the quadratic polynomial approximation can realize the prediction of cloud features at a scale of 8 seconds.

There is a big error when the quadratic polynomial approximation is applied in the forecast model of existing cloud features because of the complex concave cloud contour. The results may be greatly different from the actual cloud contour. In actual weather condition, cloud contour will change according to the wind and can't keep convex all the time. The complex concave polygons with big concavity are very common. It is necessary to apply convex decomposition to make this kind of cloud be adapted to the existing forecast model for cloud features.

There are lots of researchers studying on the convex decomposition of concave clouds. There are two

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kinds of convex decompositions for the polygons. The subdivision lines are just applied to remove the current pits when we do the convex decomposition, which is called the local subdivision algorithm. A best subdivision line is selected from all the points according to some convex rules, which is called global subdivision algorithm[6]. Ref. [7] proposed a new simple polygon subdivision algorithm called Delaunnay based on judgments on convex or concave points. It has a good application on surface reconstruction. This algorithm is not adaptable to the convex decomposition of complex concave clouds, because the complex points instead of simple straight lines make up the cloud contour. According to the relation between the neighboring concave points, Ref. [8] classified the polygons first and then realized the completely convex decomposition of polygons through applying recursive decomposition. This algorithm is efficient and the time complexity is relatively low. But the computational complexity is high. Through the comparison of various algorithms, Song Xiaomei strongly recommended using vector product method and slope method[9]. A rapid convex decomposition algorithm based on neighboring concave points bisectors was proposed by He[10], who analyzed and summarized the existing algorithms. There is no need to add new vertexes, the quantity of subdivision results is small, and the size and shape of the submaps are satisfying. This algorithm is efficient for the polygons that consist of simple straight lines, while it doesn't work well to clouds that have complex points.

This paper analyzes the characteristics of cloud contour in detail. The definition of complex concave clouds is proposed. The subdividing method for concave clouds and the corner recognition algorithms based on centroid point scattering model are proposed and simulated.

1 Definition of complex concave clouds and simple convex clouds

The ultra-short-term power prediction model based on machine vision is shown in Fig. 1. And the key to prediction for the distributed ultra-short-term PV power output is the ultra-short-term prediction for cloud features.

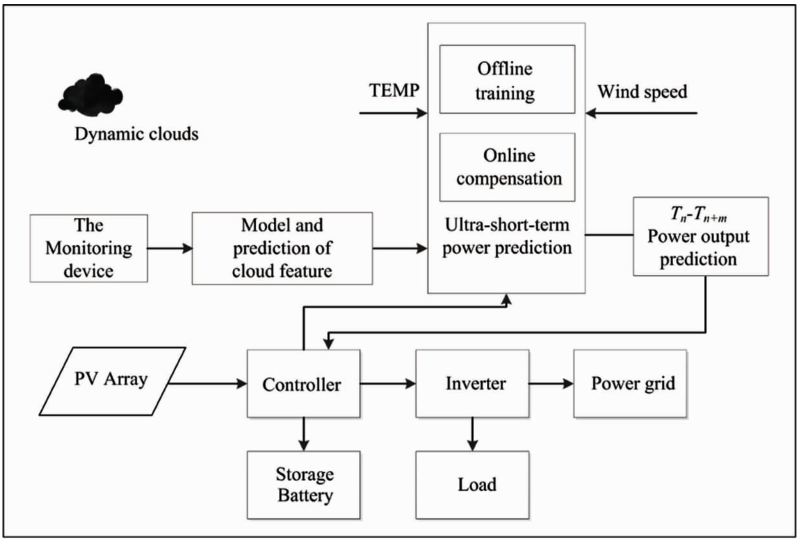


Fig. 1 Ultra-short-term power prediction model based on machine vision for distributed photovoltaic system

Cloud features can also be considered as cloud shape features, which is the visual representation on the horizontal plane projected by clouds. The cloud features directly determine the projection orientation and the shielding area of cloud shadows according to different sun elevation angle and solar azimuth. Cloud features are changing during the different phases of clouds such as growing, developing and disappearing. The changing speed and amplitude reflect the change of weather to a certain extent. The key to the cloud feature research for the ultra-short-term power prediction of distributed PV system is the modeling, identification and evolution forecast. Recently, the quadratic polynomial was mainly applied to the research of cloud prediction in meteorology. The sampling points on cloud contour are used to fit and predict the response position at next moment. Then the whole cloud contour would be predicted.

1.1 Definition of complex concave clouds contour

Cloud features in the near future can be accurately predicted by the existing cloud shape and velocity fitting models according to many cloud images in a timing series. But when there is larger concavity on cloud contour, the connection between the centroid and the outer point on the contour will have several nodes. For example, the connection between feature point F and centroid O has two nodes with the concave contour, shown in Fig. 2. Larger error will arise when quadratic polynomial approximation is applied to the forecast model of existing cloud features in this condition.

Shown in Fig. 2, the centroid is set as basic point (BP), if any rays eliciting counter-clockwise and starting from BP have more than two (including two) nodes with clouds contour, the clouds contour is defined as complex concave clouds.

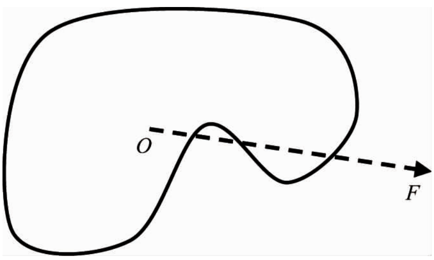


Fig. 2 The diagrammatic drawing of concave cloud

1.2 Definition of simple convex clouds

The centroid is set as BP, if any rays eliciting counter-clockwise and starting from BP have only one node with clouds contour, the clouds contour is defined as simple convex clouds, shown in Fig. 3.

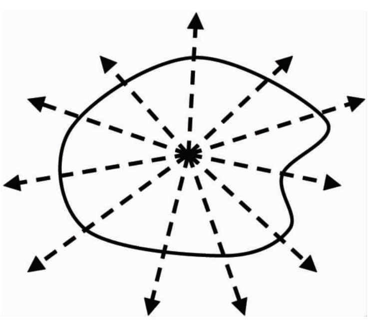


Fig. 3 The diagrammatic drawing of convex cloud

2 Convex decomposition of complex concave clouds

Essentially, cloud is a visible macroscopic phenomenon formed by countless different particle diameter vapor molecules gathering. So there are dense edge points on the contour of the cloud binary images and contour images that are obtained after threshold. The bumpiness on the contour is so tiny that it has no influence on the mathematical description and appearance recognition of cloud contour. It is unnecessary to do convex decomposition when there are too many detected points. So it is necessary to reduce the number of points through internal polygonal approximation.

2.1 Minimum polygonal approximation

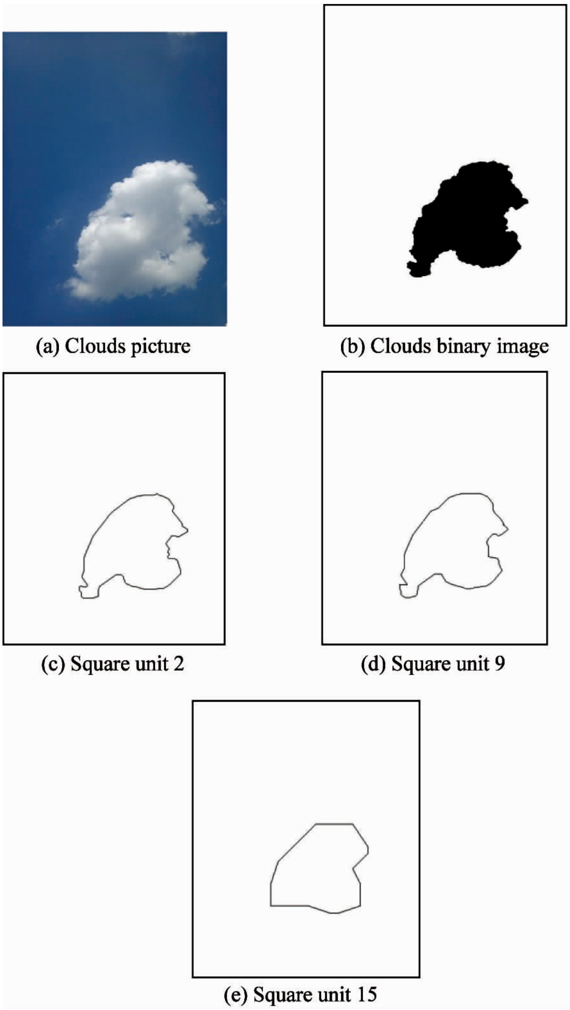
It is optimum for polygonal approximation to show the basic contour of given boundary by polylines as fewer as possible, which increases the time consuming on iterative and computational burden if more polylines are applied, while it can express the shape features of given boundary most closely. The computational burden is light if fewer polylines are applied, while it can't express features in detail. Even though there are dense edge points, and they hardly affect the recognition of contour and the quadratic polynomial approximation. Therefore, moderate minimum polygonal approximation (MPP) is adopted to approximately express the internal boundary.

MPP was first proposed by Sklansky to find a region or a boundary for simple polygon[11], who used a series of quadrangular elements (named as cell mosaics) to form an enclosed boundary. On the edge of the enclosed boundary, the quadrangular elements make up a 4-connected path. Then the boundary of the image can be represented by a polygon deduced by the quadrangular elements according to the angle at each point. Readers can refer to Ref. [12] for more detailed information. In MATLAB, MPP algorithm is mainly achieved by the following[13]:

$$[X, Y, R] = \mathrm{im2minperpoly}(f, \textit{cellsize})$$

where f is a binary image containing only a single zone. The *cellsize* determines the size of square units which are used to enclose the zone. Column vectors X and Y represent the *X-axis* and *Y-axis* that include the vertexes of MPP. The binary image enclosed by cells is represented by R.

Fig. 4 shows the clouds image, the clouds binary image and MPP images whose unit sizes are 2, 9 and 15. It is obvious that in Fig. 4 (a) there are dense points on the contour without dealing by MPP. They increase great computational burden on detection of edge points. As shown in the pictures, clouds contour still contain many details dealt by square unit 2, while some concavity lost when dealt by square unit 15, neither of them were applied. Next step is to determine the basis for evaluation that represents the effect. The position extraction and calculated velocity vector are set as the input of the ultra-short-term power prediction of distributed PV system. They have strong influence on the accuracy of the ultra-short-term power prediction. So the minimum centroid point deviation value σ is set as the basis for evaluation.



(a) Clouds picture (b) Clouds binary image

(c) Square unit 2 (d) Square unit 9

(e) Square unit 15

Fig. 4 Simulation of MPP polygon approximation

$$\sigma_n = \sqrt{(x_n - x_0)^2 + (y_n - y_0)^2} \quad (1)$$

The centroid point coordinates of clouds picture are set as (x_0, y_0), and the approximate centroid point coordinates of square unit 2, 9 and 15 are set as $(x_n, y_n)(n = 2, 9, 15)$.

In order to decrease the edge corners and iterative computational quantity, the basic information of clouds contour is shown as much as possible, when the same time σ is adopted. As shown in Table 1, square unit 9 is relatively reasonable to approximate the internal polygons.

Table 1 The centroid point deviation of different square units

	X-axis	Y-axis	σ_n
Clouds picture	219.95	304.92	/
Square unit 2	214.17	313.98	7.87
Square unit 9	212.22	312.06	10.52
Square unit 15	206.6	294.34	17

2.2 Convex decomposition of complex concave clouds

Convex decomposition of concave polygons is one of the important issues in the research of computer graphics geometry, which is widely applied in computer graphics, rapid manufacturing scan, etc. There are two basic schemes on algorithms for convex decomposition of concave polygons[10]. The first scheme aims to split the concave polygons into many Delaunnay triangles. The second scheme aims to find the pits on concave polygons, then connect these pits from split lines through some regulation. After dividing the concave polygons along split lines, you should find if any pit exists in the submaps. Repeating the algorithms until there is no pit any more. Finally, convex decomposition of concave polygons is done.

The three main steps for convex decomposition of concave polygons are shown as:

a) All the corners of concave polygons are calculated. Looking for the position of pits.

b) The split lines are determined by some regulation, and the mother figure is divided into two subfigures along the split line.

c) All the corners of subfigures are calculated. Repeating the steps until there are no pits any more. Then the convex decomposition is done.

2.2.1 Corner detection on cloud contour

Corners include all the pits and bumps. To search for the pits on contour is the biggest computational burden during convex decomposition of concave polygons. It is convenient to do corner detection on cloud contour to find pits.

Corner detection aims to find split lines which are used for convex decomposition of concave clouds. The lost corners result in the lost of split lines easily. Harris-Stephens corner detection is an improvement based on the method proposed by Moravec[14]. Its anti-noise and stability are strong, and the corners extracted are reasonable. The figure of corner detection obtained by the above mentioned method is shown in Fig. 5. The white points in the figure are the corners.

2.2.2 Recognition of pits on cloud contour

The corners that include pits and bumps detected by corner detection are signed as $p_n(n = 1, 2, 3, 4 \cdots)$ in counter-clockwise. The straight section between p_{n-1} and p_n is defined as vector a, and the straight section between p_n and p_{n+1} is defined as vector b. Vector c is the cross product generated by a and b:

$$\boldsymbol{c} = \boldsymbol{a} \times \boldsymbol{b} \quad (2)$$

Suppose that $\boldsymbol{a} = (a_x, a_y)$, $\boldsymbol{b} = (b_x, b_y)$, then:

$$|\boldsymbol{c}| = a_x \cdot b_y - b_x \cdot a_y \quad (3)$$

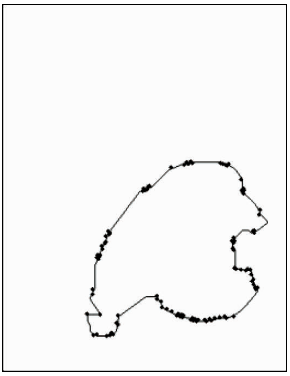


Fig. 5 The drawing of Corner detection results

And:

$$| \boldsymbol{c} | = | \boldsymbol{a} | | \boldsymbol{b} | \sin\theta \quad (4)$$

Then:

$$\sin\theta = \frac{a_x \cdot b_y - b_x \cdot a_y}{\sqrt{a_x^2 + a_y^2} \cdot \sqrt{b_x^2 + b_y^2}} \quad (5)$$

where θ stands for the angle between vector $\boldsymbol{a}$ and $\boldsymbol{b}$. The value is positive for $\sin\theta$ when angle ranges in $(0, \pi)$, while it is negative when angle ranges in $(\pi, 2\pi)$. Therefore, whether p_n is pit can refer to the value of $\sin\theta$.

2.2.3 Determination of split lines

After all the pits are detected, the next step is to determine the split lines which match with pits through certain regulation. The concave polygons can be divided into many convex polygons through appropriate regulation in the condition of the minimum amount of calculation. The regulation for split lines introduced in Section 2.2 is usually applied in simple concave polygons which contain fewer pits and polylines. There are lots of pits on the contour even though the clouds contour is dealt with the internal polygonal approximation. It has little influence on the recognition of clouds contour because most pits have small concavity. In fact, convex decomposition of concave clouds contour aims to avoid the problem described in Section 1.1. The centroid is set as the basic point. And rays eliciting from the basic point will have many nodes with clouds contour if the concavity is big enough, which will affect the accuracy of the quadratic polynomial prediction.

Therefore, split lines are determined by the clouds centroid point scattering model. The concrete algorithm is introduced as follows combined with Fig. 6. The cloud centroids O and Q are set as BP. Rays go straightly in the horizontal right direction from the BPs. There are 360 rays elicited from BP counterclockwise in the step angle of one degree. The circumferential span between two neighboring rays increasing results from the increasing distance between the centroid and cloud contour. There are N rays passing through N pits and bumps in order to avoid the omission of pits and bumps. The total quantity of rays is 360 plus N. Every ray has one node with clouds contour when it is convex contour. There are at least three nodes when the contour has larger concavity. More nodes appear if complex details are contained in cloud boundary. More complex details will not appear after dealing with internal polygonal approximation.

Therefore, there are two kinds of the determination of split lines depending on the condition of clouds.

Firstly, as shown in Fig. 6(a), the ray in the horizontal right direction starts to scan counter-clockwise. There is only one node with the contour. Then, the nodes increase to two and three, the node decreases to one finally. Every node is signed as p_n ($n = 1, 2, 3, \cdots$).

The quantity of nodes establishes a sequence: 1, 1, 1, …, 2, 3, …, 2, 1, … . The most important coordinates are the second point whose nodes are two, that is the point signed as 1 in Fig. 6(a). The ray passing through that point is the split line of the concave clouds.

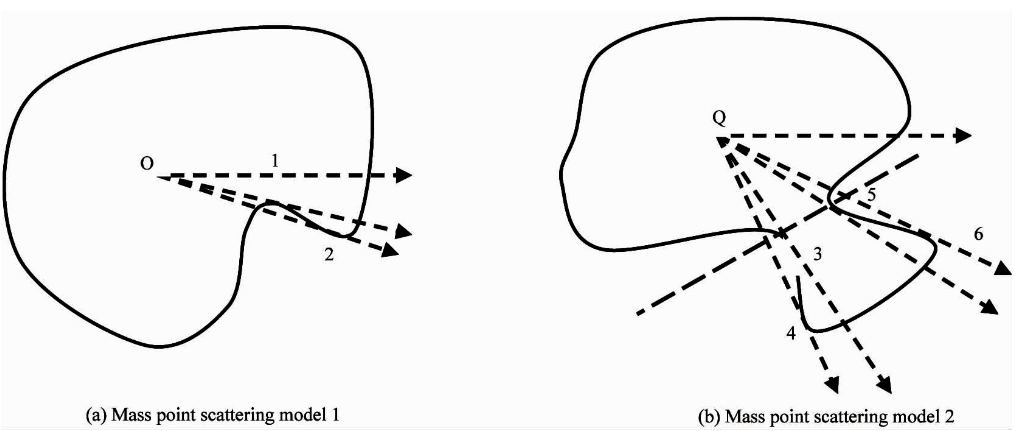


Fig. 6 The model of the center of mass point scattering

As shown in Fig. 6(b), the same scattering model is applied in scan. The sequence is 1, 1, ⋯, 2, 3, ⋯, 2, 1, ⋯, 2, 3, ⋯, 2, 1, ⋯. The most important coordinates are the second and the third points whose nodes are two, that is the point signed as 3 and 5 in Fig. 6(b). The straight line connecting points 3 and 5 is the split line for convex decomposition of clouds contour, which divides the clouds contour into two subfigures. The scattering model is applied in the two subfigures until each ray has only one note with the contour.

The clouds contour can be divided into many subfigures after the split lines are determined. Convex decomposition aiming at the quantity of nodes in the mass point scattering models is one, which means the quadratic polynomial approximation can be applied in the prediction for cloud features.

The black point in the cloud contour is the centroid, shown in Fig. 7(a). And the black line is the split line. The cloud contour is divided into three subregions along the split line. One of the sub-regions is too small and located on the edge. There is little influence on sun radiation from these edge portions. Thus the Fig. 7(b) and (c) are reasonable.

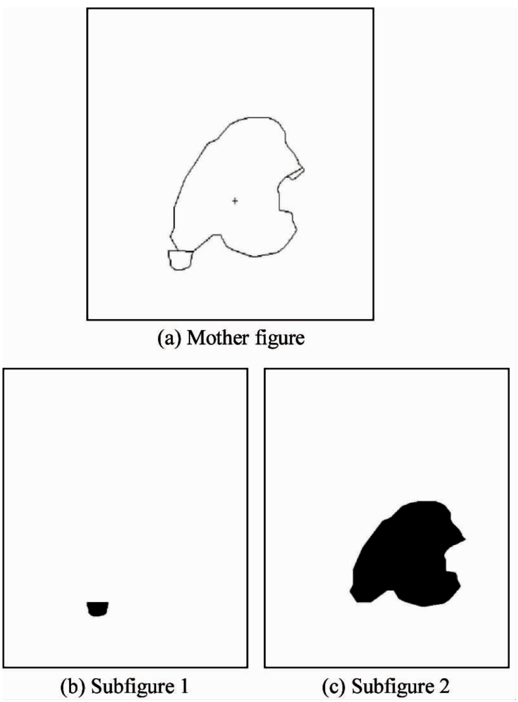


Fig. 7 The result of the convex decomposition of complex concave polygon

3 Algorithm validation and discussion

3.1 Convex decomposition of cloud

This algorithm is applied in the simulation for the convex decomposition of another concave cloud in order to testify the effect and applicability of the convex decomposition on complex concave clouds contour. The cloud picture is shown in Fig. 8.

Fig. 8 The picture of the complex concave cloud

Image preprocessing including mathematical morphology is applied in Fig. 8, which aims to fill the broken holes, smooth the profile and eliminate influences caused by chiffon-like clouds. The cloud binary image is shown in Fig. 9.

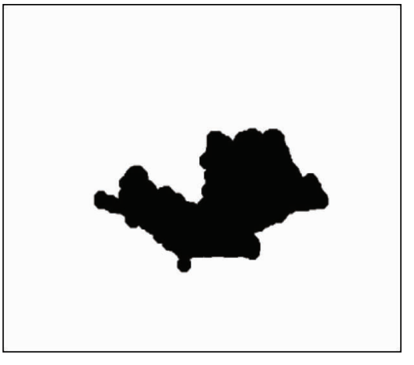


Fig. 9 The profile after preprocessing

The features of clouds contour are extracted firstly according to the internal polygonal approximation described in Section 2.1. Simple polylines are applied to approximate the clouds contour. The black point represents the position of mass point of clouds. The clouds boundary extraction and internal polygon approximation are shown in Fig. 10 and Fig. 11.

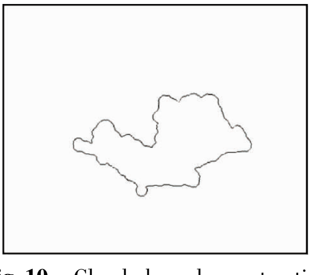


Fig. 10 Clouds boundary extraction

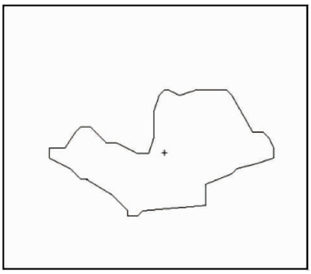


Fig. 11 Internal polygon approximation

The split line of convex decomposition is obtained through pits recognition and principle of certainty for split lines described in Section 2.2. The internal straight line is the split line, shown in Fig. 12.

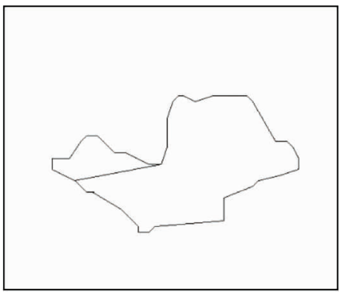


Fig. 12 The split line of convex decomposition

Finally, Fig. 12 is divided into two subfigures by the split line, shown in Fig. 13. Fig. 13(a) and (b) satisfy the definition of simple convex clouds put in Section 1.2. They are adaptable to the ultra-short-term power prediction of distributed PV system based on mathematical models for cloud features.

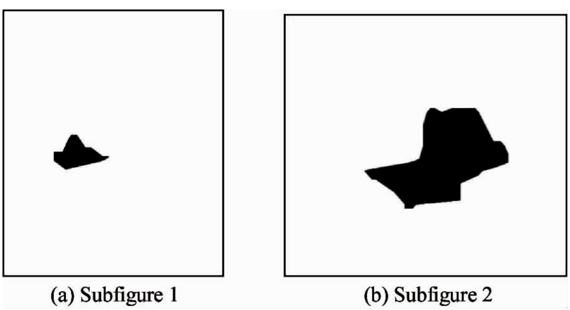


Fig. 13 The result of convex decomposition

3.2 Comparison and discussion

As defined in Section 1, a complex concave cloud must have at least one ray from the centroid to the outside, which has more than one cross nodes with the clouds contour. This definition is suitable for the application of sheltering area calculation for PV power station ultra-short-term output prediction. Actually, there are different definitions for different applications. In Ref. [10], the authors used the concave polygon from geometry for earthwork calculation. Thus, the concave polygon is decided by the inner angle at all the vertexes P_i.

It is clear that the definition for concave shape cloud in this paper is entirely different from conventional geometry terminology. Then, the decomposition algorithm has its own advantages for the PV system ultra-short-term power output prediction, such as time complexity and decomposition part numbers. For the cloud shown in Fig. 8, it is decomposed into two subfigures using the proposed method, consuming 0.01s to segment the image into two convex clouds. The image size is 425 (345 pixels and the algorithm was programmed in MATLAB and executed on an ASUS K50I laptop computer with Pentium Dual-core 2.2GHz CPU and 2G RAM. While using the rapid convex decomposition algorithm based on neighboring concave points bisectors[10], it needs 2.32s to segment the same cloud image into 12 parts shown in Fig. 14, using MATLAB on the same computer. The great difference of time-consuming between the two methods lies on the algorithmic complexity and decomposition sub-image numbers.

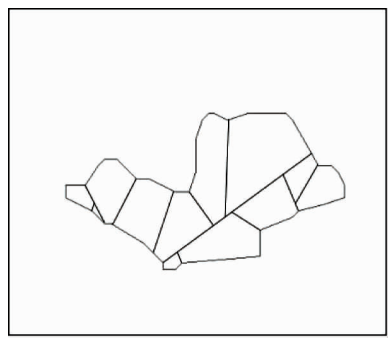


Fig. 14 Decomposition results of algorithm in Ref. [10]

It can be seen from the above analysis that the proposed cloud image decomposition algorithm can segment the concave clouds into convex images as quickly as possible, without redundant or over decomposition for the PV ultra-short-term power output prediction. And the time needed for the decomposition process is in the level of micro-second, which is critical and suitable for the expected application of the proposed algorithm.

4 Conclusions

The sun radiation received by the PV panels decreases greatly because of clouds sheltering, which causes the violent fluctuation of the power output for distributed PV system. This paper analyzes convex decomposition of concave clouds on the basis of the ultra-short-term power prediction of distributed PV system. The purpose and expected application is to eliminate the negative effects on the ultra-short-term power prediction of distributed PV system, which result from complex concave clouds.

(1) The mass point scattering model is established, which helps to define complex concave clouds and simple convex clouds.

(2) The minimum polygonal approximation is adopted to establish the concave clouds contour models because the concave clouds contour is complex after preprocessing.

(3) The subdivision lines of convex decomposition for the concave clouds are determined by the centroid point scattering model and centroid angle function. The regulation is proposed.

The result of MATLAB simulation indicates that the proposed algorithm can accurately detect the cloud contour corners and realize the concave points recognition. The established model can make the convex decomposition of the complex concave clouds completely and rapidly, making it available for the existing prediction algorithm for the ultra-short-term power of distributed PV system based on the cloud features.

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