A Working Pattern Recognition Method For Satellite Power System Based On Uncertain Data Clustering Strategy

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***Abstract*—The power system plays a major role in the maintenance of working properly for satellite. As there are many working loads and different working attitudes, the power system has many diverse working patterns. So it is very critical to recognize the working patterns accurately. However, due to the measurement error, environmental interference, and other uncertainty factors, the output voltage of the satellite power system has remarkable uncertainty. If we did not consider the uncertainty and various working patterns, poor recognized result will be generated. For this issue, we proposed a working patterns recognition method for satellite power system based on uncertainty data clustering strategy. In this method, we firstly utilize uncertainty data clustering strategy to modeling working patterns. Then during pattern recognition stage, we calculate the distances between uncertain cluster centers and the measurement data. The experimental results of actual power system data illustrate the validation and feasibility of our proposed method.**

Keywords-Satellite Power; Working pattern recognition; Uncertainty data; clustering

I. INTRODUCTION

The satellite power system plays a very important role in maintenance of working properly under different environments [1-2]. Generally, we monitor the output voltage of the power system to recognize the working patterns and diagnose its health conditions [2-3]. However, due to the impact of some factors, satellite power system has some different working patterns. On one hand, in the space, satellite need to adjust its attitude, or due to the rotation, its solar panel may face the sun or away from the sun. So the output voltage may change from time to time. On the other hand, satellite has many working loads. Their working status determines different working patterns of satellite power system.

Except for different working patterns, there are some negative factors [4], i.e. the environment noise and interference, measurement error, or the attitude minimum change of the satellite. These negative factors lead to different levels of uncertainties in the output voltage values of satellite power system. If we do not consider these working patterns with uncertainties, wrong recognition will be gained.

Currently, there are some recognition methods, including Fuzzy C-means (FCM) based method [3, 5], amplitude based method [6, 7], statistical means based method [8, 9], and statistical standard deviation method [10, 11]. However, they have not considered the data uncertainty and variety of working patterns, the recognition accuracy is low. For this problem, in this paper, we consider the different working patterns with different levels of uncertainties of satellite, and utilize uncertain data clustering to recognize the working pattern on line. So as to improve the recognition accuracy.

II. RELATED WORKS

The modelling and diagnosis of the application system have attracted many scholars' attention recently years. They presented satellite modelling, fault diagnosis and working pattern recognition methods. For the working pattern recognition and diagnosis, there are various methods including the FCM-based method [3], amplitude based method [6], statistical means based method [9], and statistical standard deviation method [11].

Literature [1] proposed a modelling method and diagnostic technique for the power system of the satellite. It constructed the power model in a component-based modelling manner. The special knowledge is required. Consider the fault evolution, coupling, unreliable tests and other problems, [2] gave a framework for model based diagnosis to decrease the diagnostic uncertainty for satellite. The framework is known as LYDIA-NG, which combined several diagnostic, simulation and active-testing algorithm.

To improve fault diagnosis accuracy of power transformer, [3] presented a diagnosis model based on FCM clustering algorithm and improved principle component analysis (IPCA), however the complexity is higher. Considering duplicate and conflicting objects during decision table, [5] combined rough set theory (RST), single value decomposition (SVD), and FCM to establish a flexible matching model. For heterogeneity in a medium structure always increases the non-linear effects in the long-wave perturbations. [6] proposed a method for diagnostics of the properties of medium components of long non-line

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waves. It utilized long-wave of finite amplitude to conduct medium structure for diagnostics. Using small amplitude transient analysis, [7] proposed online diagnostics of fuel cells. Literature [8] studied the influence of mechanical errors in diagnostics applications by means of statistical analysis. To improve the computational cost, [9] presented a method to recognize abnormal patterns of multivariate processes. Literature [10] calculated statistical property feature vector composed of range, mean, standard deviation, entropy, then utilize least squares support vector machine (LSSVM) to diagnostics of the incipient faults. For fault diagnostics in oil filled electrical equipment, [11] reviewed triangle and the possibility of alternatives. For each fault class, the standard deviation is calculated and compared with that for Duval triangle to identify the fault.

III. THE WORKING PATTERN RECOGNITION METHOD BASED ON UNCERTAIN DATA CLUSTERING

In this section, we first illustrate the uncertain data expression in term of interval data. Then we describe statistical calculation of the satellite power system output voltage with slide window strategy. Lastly, we illustrate the working pattern recognition method based on uncertain data clustering strategy, and detail function of sub-components.

A. *Interval data* [12-13]

Definition 1: Given two real data x_L , $x_R \in \mathbf{R}$, and $x_L \le x_R$, we can call the collection $x=[x_L,\ \ x_R]$ an interval data. As illustrated in Fig. 1(a), x_L is the lower bound of interval data *x*. x_R is the upper bound of interval data *X*.

Definition 2: For an interval data $x=[x_R,\ \ x_R]$, we treat $m_X=(x_L+x_R)/2$ as the mid-point of interval data *x*, and $r_X=(x_R-x_L)/2$ as the radius of interval data *x*. we can have the following equations.

$$x_L = m_x - r_x \tag{1}$$

$$x_R = m_x + r_x \tag{2}$$

So the interval data *X* can be expressed as $x=[m_x-r_x,\ \ m_x+r_x]$.

Definition 3: For a Given two interval data $x=[m_x-r_x,\ \ m_x+r_x]$, and $y=[m_y-r_y,\ \ m_y+r_y]$, $m_x, m_y \in \mathbf{R}$, $r_x, r_y \in \mathbf{R}$, the geometrical relationship between *x* and *y* can be illustrated in Fig. 1.

When they are separated, as shown in Fig. 1(a), the minimum distance is $|m_x-m_y|-r_x-r_y$, and the maximum distance *d* is $|m_x-m_y|+r_x+r_y$.

When they are adjoined and overlapped, as shown in Fig. 1(b) and Fig. 1(c), the minimum distance is 0, and the maximum distance *d* is $|m_x-m_y|+r_x+r_y$.

When the interval data *X* data contains interval data *Y*, as shown in Fig. 1(d), the minimum distance is 0, and the maximum distance *d* is $|m_x-m_y|+r_x+r_y$.

So we can see that the distance between them is also an interval data. We define the distance *d* between *X* and *Y* as follows.

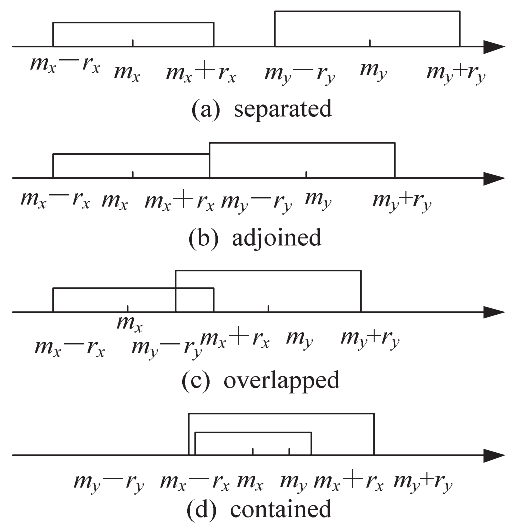


Figure 1. Geometrical relationship between interval data

$$d=[d_{\min},\ d_{\max}] \tag{3}$$

$$D_{\min}=\begin{cases}|m_x-m_y|-\alpha_x-\alpha_y, & |m_x-m_y|-\alpha_x-\alpha_y \ge 0\\ 0, & |m_x-m_y|-\alpha_x-\alpha_y<0\end{cases} \tag{4}$$

$$D_{\max}=|m_x-m_y|+\alpha_x+\alpha_y \tag{5}$$

B. *Statistical calculation with sliding window strategy*

As the output voltage of the satellite power system is generated in term of data stream, we adopt the sliding strategy to perform statistical calculation on the output voltage data stream. More specifically, we perform calculation on the voltage data within a sliding window with specific time range, which slides with the time changing. We focus on the statistical means m_y and statistical standard deviation r_y , and express the distribution characteristic in term of interval data $y_t=[m_y-r_y,\ \ m_y+r_y]$. Here *t* is time stamp of current time *t*. And can be calculated as follows.

C. *Working patterns recognition based on uncertain data clustering processing*

Considering the variety of working patterns and uncertainty of power output voltage, we utilize uncertain data clustering algorithm to perform working pattern reorganization. In the method, we firstly conduct working pattern modelling through statistical calculation strategy, and express the distribution characteristics of working patterns in term of interval data. Then we utilize uncertain data clustering algorithm to recognize the working patterns of satellite power system.

1) Working Pattern modelling

As the power output voltage is one-dimensional signal, we also consider the uncertainty of power output voltage and explore interval data to model the working patterns. We first perform statistical calculation of each working patterns. As we know, suppose the measurement data obey the normal distribution, and μ is the statistical mean, and σ is statistical standard deviation. The probability of the data been in the interval $[\mu-\sigma,\ \mu+\sigma]$ is 68.3%. And the probability of the data been in the interval $[\mu-2\sigma,\ \mu+2\sigma]$, and $[\mu-3\sigma,\ \mu+3\sigma]$ is 95.4% and 99.7%, respectively. So the statistical interval can be generally expressed as $[\mu-k\sigma,\ \mu+k\sigma]$, here k is coverage factor, and $\{k\in\mathbf{R}|0\le k\le 3\}$.

Without loss of generality, suppose there are N working patterns, $N\in\mathrm{N}$. For the ith working pattern, the statistical mean and statistical standard deviation is μ_i and σ_i , respectively. We treat each working pattern as a cluster, And the cluster center c_i can be represented as $c_i=[\mu_i-k\sigma_i,\ \mu_i+k\sigma_i]$. We also consider the valid range of cluster, which means that if the data is located out of $3\sigma_i$ of cluster center c_i, we treat it as an outlier. In the same way, we conduct statistical calculation and clustering center representation of other working patterns. We can the overall cluster centers as S={[$\mu_1-k^*\sigma_1$, $\mu_1-k^*\sigma_1$], [$\mu_2-k^*\sigma_2$, $\mu_2+k^*\sigma_2$], …, [$\mu_i-k^*\sigma_i$, $\mu_i+k^*\sigma_i$],…, [$\mu_N-k^*\sigma_N$, $\mu_N+k^*\sigma_N$]} , their radius R={ r_1 , r_2 , …, r_i , …, r_N }and the corresponding working patterns M={ m_1, m_2, …, m_i, …, m_N }.

2) working pattern recognition through Uncertain data clustering strategy

We use online clustering strategy to recognize the work pattern. More specifically, we calculate the distance { d_i } between the statistical information expressed in interval data y and the clustering centers { c_i }. We determine the minimum distance d_j within the specific radius { r_i }, and treat the corresponding working pattern m_j as the working pattern estimation value.

Consider the distance d_i is interval data, to combine the distance metric and algorithm organically, and express every possible distance square value between minimum value and maximum value, we adopt the correlation factor λ , and $\{\lambda\in\mathbf{R}\,|\,0\le\lambda\le 1\}$. And the square distance can be calculated as follows.

$$d^2(c_i, y)=\lambda d^2_{\min}(c_i, y)+(1-\lambda)d^2_{\max}(c_i, y) \qquad (7)$$

Considering there are some unknown working patterns, which have not been recognized during working pattern modelling stage. We resort to temper cluster window to store the outlier data, which does not belong to any working patterns. There are two cases. In one case, the outlier may contain gross error, the outlier will not repeat any more, and it will be discarded in the later processing. In the other case, the outlier is belonging to unknown working patterns. That's means that the outlier will come repeatedly, and these outliers will comprise a new cluster in the temper cluster window. So the pseudo code of the working pattern recognition based on uncertain data clustering (WPRUDC) is illustrated as follows.

```
Algorithm: WPRUDC ( )
Input:  y_t , k, λ, { c_i }, { r_i } ( 0≤i≤N )
Output: m_y  // the working pattern estimation result
{ temp_c_i }={∅}
do while ( y_t )
   for i =1 to N
      calculate d^2(c_i, y_t)
   end
   determine min( d^2(c_i, y_t) )=d^2(c_j, y_t)
   if ( d(c_j, y_t) < r_j )
      m_y = m_j
   else
      if ( temp_c_1 = ∅ )
         temp_c_1 = y
      else
            if ( y_t ∈ {temp_c_i} )
               if size( temp_c_i )>4
                  delete old cluster center
                  update temp_c_i to cluster center
                  m_y = u_j
               else
                  size( temp_c_i )++
                  m_y = ∅
               end
         else
               m_y = ∅
               if ({ temp_c_i } is full)
                  deleted old temp cluster center
                  temp_c_old = y_t
               else
```

$temp\_c_{i+1} = y_t$

end

end

end

The computing complexity of the proposed algorithm WPRUDC is O(t), which is linear the length of input data y_t. So it can recognize the working pattern of the satellite power system on-line.

IV. Experimental Evaluation

We will evaluate the feasibility and validation of our proposed working pattern recognition method based on uncertain interval data clustering strategy. We first setup the experiment environment. Then we conduct experiments to evaluate the performance of the proposed method.

A. Experiment setup

1) Experiment data

We adopt the actual satellite power output voltage data to evaluate our proposed method. The data is from our research partner company. As affected by many factors, the satellite power system output voltage changes from time to time, as shown in Fig. 2. So the working pattern changes with time. And the real working pattern is shown in Fig. 3.

As the voltage data scale is generated in the form of data stream, so we conduct statistical calculation on it with time sliding window. and the width of the time sliding window is set to be 200.

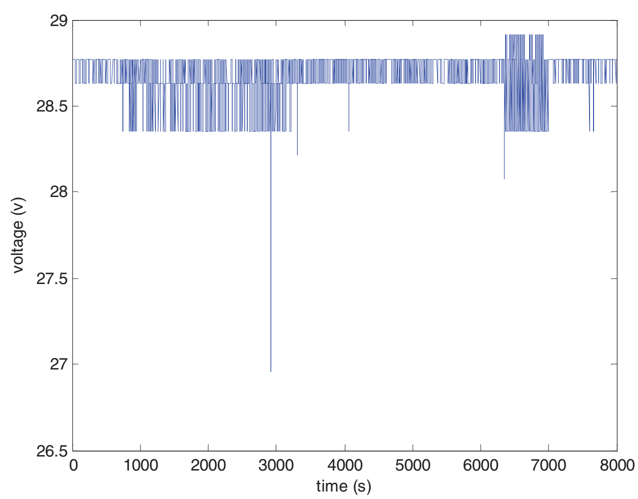


Figure 2. The satellite power system output voltage

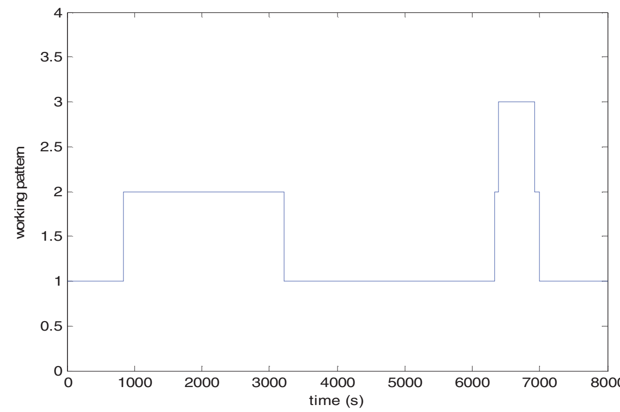


Figure 3. The working pattern of satellite power system

2) Evaluation Metric

We evaluate the performance of our proposed satellite power working pattern recognition method in term of recognition accuracy and recognition efficiency. The recognition accuracy can be calculated the difference between real working patterns and its real values. We evaluate the recognition efficiency in term of recognition processing time.

The configuration of evaluation platform is follows. CPU: Intel i7 720QM@1.6GHz, 8G RAM, Window 7 64bit. Evaluation environment: Matlab 2010.

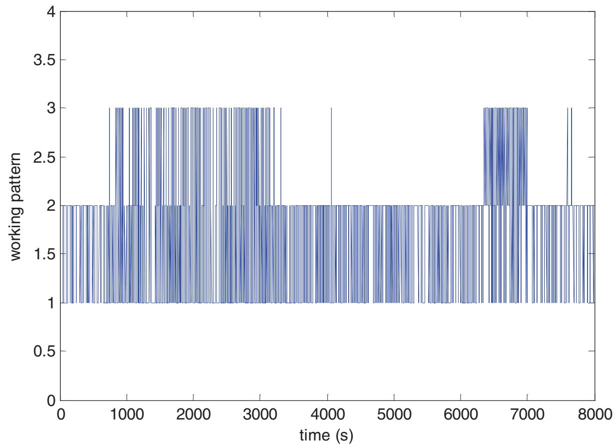
3) Reference methods

We adopt fuzzy c-mean (FCM)-based recognition method [3, 5], amplitude-based recognition method [6, 7], statistical means-based recognition method [8, 9], and statistical standard deviation-based recognition method [10, 11] as the reference methods. We will compare their recognition accuracy and recognition efficiency with our proposed method.

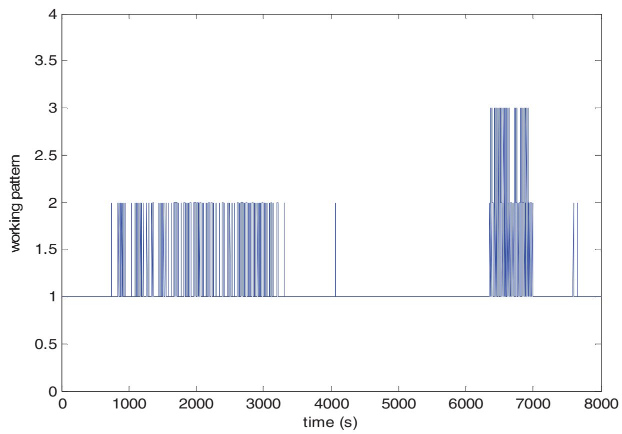
To compare fairly, we do not implement the reference method completely, but to utilize the processing strategy in our reference methods.

B. Recognition performance evaluation

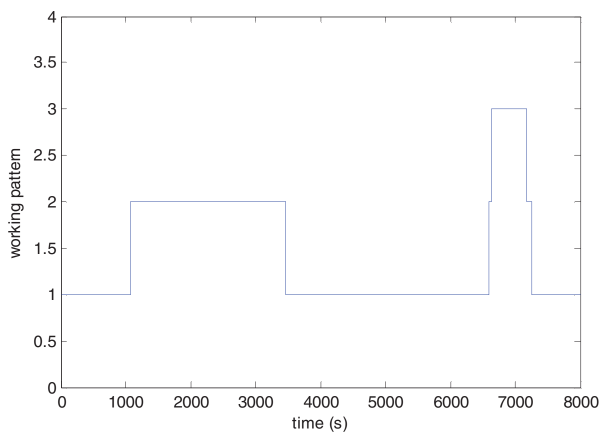
We utilize the FCM-based method, amplitude-based method, statistical means-based method, statistical standard deviation-based method, and our proposed recognition method to process the satellite power output voltage data. We first calculate the statistical information including the statistical means and standard deviation of the data. Then we adopt these methods to perform working pattern recognition. And we compare their performance in term of recognition accuracy and recognition efficiency. We illustrate the recognition accuracy in Fig. 4., and show the recognition accuracy in Table I. The recognition efficiency is presented in Table II.



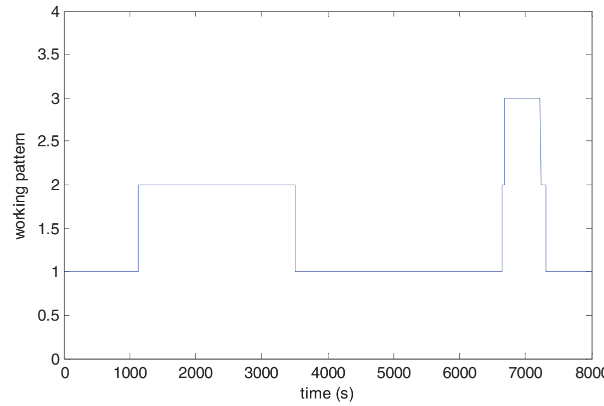
(a) Recognition result of FCM-based method



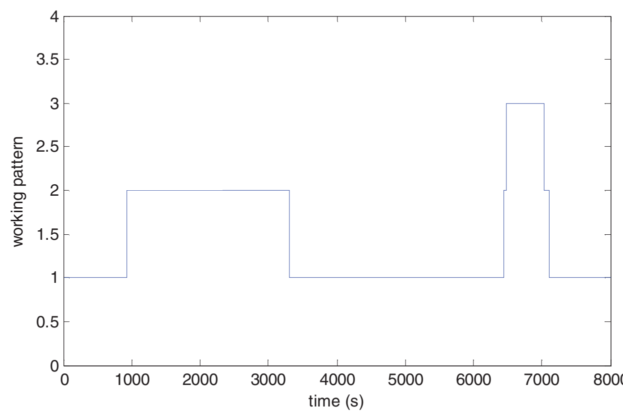
(b) Recognition result of amplitude-based method



(c) Recognition result of statistical mean-based method



(d) Recognition result of statistical deviation-based method



(e) Recognition result of uncertain data clustering-based method

Figure 4. The working pattern recognition result of methods

TABLE I. THE RECOGNITION ACCURAYC OF METHODS

Method	FCM-based	Amplitude-based	Statistical Mean-based	Statistical Standard-based	Uncertain Clustering
Accuracy	0.6498	0.6801	0.9266	0.9243	0.9621
Improvement	48.06%	41.46%	3.83%	4.09%	-

From Fig. 4 and Table I, we can see that our proposed uncertain data clustering based recognition method have higher accuracy than that of other methods. More specifically, relative to FCM-based, Amplitude-based, statistical means-based, and statistical standard deviation-based method, our proposed method can improve the recognition accuracy at the scale of 48.06%, 41.46%, 3.83%, and 4.09%. That owes to the proposed method consider the variety of working pattern and data uncertainty, and utilize the clustering-based recognition method.

From Fig. 4 and Table I, we can also draw conclusion that the statistical based methods including statistical mean-based, statistical standard deviation-based and our proposed method have higher recognition accuracy than FCM-based and amplitude-based method. That mainly because statistical calculation could get the main characteristic of the satellite power output voltage data.

TABLE II. THE RECOGNITION EFFICIENCY OF METHODS

Method	FCM-based	Amplitude-based	Statistical Mean-based	Statistical Standard-based	Uncertain Clustering
Efficiency	0.7332 s	0.0156 s	0.4212 s	1.1388 s	1.4976 s

Table II illustrates the recognition efficiency of different methods. We evaluate the recognition efficiency in term of recognition processing time. From Table II, we can see that the processing time of our proposed method is higher than that of the other methods. That is because there are uncertain calculation and clustering processing of the proposed method. We also see that the statistical based methods including statistical mean-based, statistical standard deviation-based and our proposed method have the processing time at the same scale. If we comprehensively consider the recognition accuracy and efficiency, our proposed method has higher advantage to recognize the working pattern of the satellite power system.

V. CONCLUSION

To recognize the working pattern of the satellite power system, we propose a recognition method based on uncertain data clustering algorithm. In this method, we considered the variety of working patterns and data uncertainty, and adopt interval data to express the statistical distribution information, we propose and utilize the WPRUDP algorithm to cluster uncertain power output voltage data. We conduct experiments to evaluate the validation and feasibility of our proposed method. And the experimental results illustrate the feasibility and validation of our proposed method. And the working pattern recognition method could be applied in the satellite power system.

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