Statistical control chart based harmonic amplification detection

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Abstract. With the rapid growth of nonlinear and fluctuating loads such as high-speed railways and converter stations, the problem of harmonic pollution is becoming more and more serious. The economic loss and social impact caused by harmonic amplification are increasingly prominent. On-line harmonic amplification detection with power quality monitoring system can identify problems and take measures in time. This paper proposes a method for online recognition of harmonic amplification based on statistical control chart. Firstly, based on the recent data the steady-state Xbar-S statistical control chart is constructed, by which the online data is identified whether it is abnormal. Secondly, it detects a harmonic amplification event by comparing its cumulative features containing Continuous time and distortion level of abnormal data segment with thresholds. The effectiveness of the method is verified based on the measured data.

1. Introduction

With the rapid growth of nonlinear, fluctuating loads such as high-speed railways, renewable energy generations, and converter stations, and the large number of applications of high-frequency switches, harmonic pollution problems have become increasingly prominent [1-4]. On the other hand, the structure of the power system is becoming more and more complex, and compensation devices are more likely to induce harmonic resonance, which causes continuous harmonic amplification. Harmonic amplification seriously affects the safe and normal operation of electrical equipment, and even damage them [5, 6]. Therefore, how to effectively identify harmonic amplification events and take reasonable measures in time through online analysis of power quality monitoring data is of great significance.

After years of exploration and accumulation, the monitoring and analysis technology of the domestic power quality monitoring system has become more and more perfect. The State Grid Corporation has built a network-wide power quality monitoring system covering 27 provinces [7], focusing on monitoring access of electric railways, wind power, photovoltaics, converter stations and other disturbance sources. The monitoring indices contain all power quality indices such as voltage deviation, frequency deviation, three-phase unbalance, harmonics and inter-harmonics, flicker, voltage sag/swell and so on.

At present, the analysis methods of power grid harmonic amplification mainly include mechanism analysis methods [8, 9] and statistical analysis methods based on monitoring data [10]. The former studies the network parallel resonance law using eigenvalues and eigenvectors worked out from the system node admittance matrix decomposition. The literature [8] analyzes the harmonic amplification
based on the singular value decomposition theory, but the accuracy of this method depends on the estimation of harmonic impedance. It is difficult to obtain complete grid parameters from the actual running grid, and more difficult to implement. The latter methods detect harmonic amplifications based on harmonic monitoring data by the means of hopping amplitude when transient event occurs exceeding an empirical threshold. Ref. [10] sets the hopping threshold before and after the transient event to 0.7%. But the fixed threshold approach is prone to misjudgment in the grid contains unknown disturbance sources.

In this paper, an online detecting harmonic amplification method based on Xbar-S statistical control charts is proposed. The method first constructs steady-state Xbar-S statistical control charts based on the recent monitoring data. Secondly, it detects a harmonic amplification event by calculating its cumulative features which contain continuous time and distortion level exceed thresholds. The algorithm does not depend on the grid parameters and is highly implementable.

2. Harmonic amplification detection based on Xbar-S statistical control charts

Statistical Control Chart is a process control theory based on data probability and statistics. It was founded in 1924 by WA Shewhart [11], which has a very important position in the field of product quality control. China has also promulgated relevant national standards (GB/T 17989-2000, GB/T 4091-2001, etc.). The Xbar-S control chart is a representative statistical control chart, which has advantages of strong anti-randomness and high recognition rate [12]. This paper is based on the statistical control chart to identify harmonic amplification events. The overall flow of the algorithm is shown in figure 1, which is divided into two major modules: constructing steady-state Xbar-S statistical control charts and harmonic amplification online detection. First, it establish a corresponding steady-state control chart for each frequency of each monitoring point. Second it extract the online data and identifies the harmonic amplification event by the means of determining whether it is continuously abnormal based on the stability control charts and the distortion is severe.

![Figure 1. The overall flow of detecting harmonic amplification method.](image-url)
2.1. Constructing steady-state \( \bar{X} \)-S statistical control charts

According to the recent historical monitoring data of the monitoring point, the \( \bar{X} \)-S control chart of each frequency of the monitoring point is constructed. That is to say, each frequency of each monitoring point corresponds to a statistical control chart, and at least every three days to extract new data to update all control charts, to ensure that the state of the control chart can characterize the quasi-real-time state of the grid operation, The process of constructing or updating the control chart is shown as in Figure 2.

**Figure 2.** Constructing steady-state \( \bar{X} \)-S statistical control charts.

Specific steps are as follows:

Step 1: Prepare recent historical data and group the data.

The recent historical data of the monitoring points are grouped. It is assumed that the data is divided into \( m \) groups, and the number of data points of each group is \( n \), where \( m \) and \( n \) need to satisfy \( m \geq 25 \), \( n > 2 \). The value of \( n \) depends on the analysis window width. Because of the strong randomness of the harmonic data, the value of \( n \) cannot be too large. The test results show that it is more effective to construct the stability control chart for the harmonic voltage data with \( n = 5 \).

Step 2: Calculating statistical eigenvalue.

Calculate the mean and standard deviation of each group of data. Assuming a total of \( m \) groups, data points of each group is \( n \), then the calculation formula of the mean value \( \bar{X}_i \) and standard deviation \( S_i \) of the \( i \)-th groups follows: \( \bar{X}_i = \frac{1}{n} \sum_{j=1}^{n} x_{ij} \), \( S_i = \sqrt{\frac{\sum_{j=1}^{n} (x_{ij} - \bar{X}_i)^2}{n-1}} \), where \( x_{ij} \) is the \( j \)-th data point of the \( i \)-th group.

Step 3: Calculating the S statistical control parameters and drawing the S statistical control chart.
Calculate the mean $\overline{X}$ and the mean standard deviation $\overline{S}$ of all groups, and the calculation formula is shown as follows:

$$\overline{X} = \frac{1}{m} \sum_{i=1}^{m} \overline{X}_i, \overline{S} = \frac{1}{m} \sum_{i=1}^{m} S_i.$$  

Calculate the upper control limit (UCL), center line (CL), and lower control limit (LCL) of the standard deviation chart (S chart). The formula is as follows:

$$\text{UCL}_S = B_4 \overline{S} \quad (1)$$
$$\text{CL}_S = \overline{S} \quad (2)$$
$$\text{LCL}_S = B_3 \overline{S} \quad (3)$$

If $n>25$, the coefficients $B_3$, $B_4$, and $C_4$ are calculated as follows:

$$B_3 = 1 - \frac{3}{C_4 n^{0.5}} \quad B_4 = 1 + \frac{3}{C_4 n^{0.5}} \quad C_4 = \frac{4(n-1)}{4n-3}$$

If $2<=n<=25$, the coefficient can be found in the parameter value table (GB/T 4091-2001). When $n=5$, $C_4=0.940$, $B_3=0$, $B_4=2.089$.

Drawing a standard deviation control chart, and judge whether the chart are stable by the means of the standard deviation $S_i$ of all groups is between $\text{UCL}_S$ and $\text{LCL}_S$ of S chart. If stable, proceed to step 4. Otherwise, it removes the unstable group and add new data group from the historical data, reaching the previous number of groups and then returns to step 2.

The criteria for judging stability are as follows:

1. The number of 25 consecutive points beyond $\text{UCL}_S$ or $\text{LCL}_S$ is 0.
2. The number of 35 consecutive points beyond $\text{UCL}_S$ or $\text{LCL}_S$ is less than or equal to 1.
   It should start from the criterion 1 and if it is not stable, proceed to criterion 2.

Step 4: Calculating the $\overline{X}$ statistical control parameters and drawing the $\overline{X}$ control chart

Calculate the upper control limit (UCL), centre line (CL), and lower control limit (LCL) of the mean chart ($\overline{X}$ chart). The formula is as follows:

$$\text{UCL}_X = \overline{X} + A_3 \overline{S} \quad (4)$$
$$\text{CL}_X = \overline{X} \quad (5)$$
$$\text{LCL}_X = \overline{X} - A_3 \overline{S} \quad (6)$$

If $n>25$, the coefficient $A_3 = \frac{3}{C_4 \sqrt{n}}$. If $2<=n<=25$, the coefficient can be found in the parameter value table (GB/T 4091-2001). When $n=5$, $A_3=1.427$.

Drawing $X$ chart and whether $\overline{X}_i$ of all groups exceed $\text{UCL}_X$ or $\text{LCL}_X$ is employed to determine if it is in a stable state. If stable, the steady-state Xbar-S control chart is constructed. Otherwise, it removes the unstable group and add new data group from the historical data, reaching the previous number of groups and then returns to step 3.

2.2. Harmonic amplification online detection

The real-time monitoring data of each frequency harmonic of important monitoring point is extracted online, and the corresponding steady-state Xbar-S control chart obtained in the previous section is used to identify whether it is abnormal. And then it extracts cumulative features of the continuous abnormal time and the distortion level are determined to if the harmonic amplification occurs, and performs early warning. The specific process of detecting a harmonic amplification event is shown in Figure 3. Specific steps are as follows:

Step 1: Extract a group of real-time data of a certain frequency harmonic of a monitoring point, and calculate the statistical feature values.

A group of real-time data of a certain frequency harmonic is extracted. Like the control chart data group, continuous n data points make a group, and calculate its statistical characteristic values, that is, the mean value and the standard deviation.

Step 2: Use the steady-state statistical control chart to identify whether the statistical characteristic values of the group are abnormal.
The statistical characteristic values of the group are plotted on the corresponding steady-state Xbar-S control chart, where the mean value is plotted on the Xbar control chart, and the standard deviation is plotted on the S statistical control chart. It is noted that since the harmonic amplification only crosses the upper control line, the basis for abnormal judgement is that the mean or standard deviation crosses the upper control line, and as long as one of them crosses the line, the group is considered abnormal.

Step 3: Extract cumulative features and determine whether it is a harmonic amplification event.

The cumulative feature to be extracted includes: the duration of the continuous abnormal groups and the average increase ratio describing distortion level, which is first proposed in this paper. If the continuous abnormal duration exceeds a certain threshold (10 minutes), and the average increase ratio in the abnormal segment is greater than a certain threshold (1.8), it can be considered as a harmonic amplification event. The average increase ratio R is defined as follows:

\[ R = \frac{\bar{X}_c}{CL_{\bar{X}}} \]  

where \( \bar{X}_c \) represents the average value of the data in the last consecutive abnormal time period, and \( CL_{\bar{X}} \) represents the centre, line of the \( \bar{X} \) control chart.

3. Example analysis

According to the actual monitoring data in a certain area of China, verify the feasibility of the method proposed in this paper. The grid topology is shown in Figure 4, including substation A, substation B, substation C, substation D, substation E and substation F. The voltage level ranges from 400V to 500kV. Each substation is equipped with monitoring points, of which the substation A is directly connected to the Converter Station.

![Converter Station](Substation A 500kV - Substation B 220kV I - Substation C 35kV II - Substation D 10kV II - Substation E 10kV II - Substation F 10kV I)

Figure 4. Topology of a certain area of Shanghai.

One-day trend of 11th harmonic voltage content rates of substation D and substation E on May 23, 2014, which are as shown in Figure 5 and Figure 6:
Figure 5. One-day trend of 11th harmonic voltage content rates of substation E.

Figure 6. One-day trend of 11th harmonic voltage content rates of substation D.

Where the blue line represents phase A, the green represents phase B, the red represents phase C.

It set the Xbar-S control chart input parameters, m=25, n=5. Based on the time series data, use the above method to construct the Xbar-S control chart of the 11th harmonic of the substation D and the substation E respectively. Due to the three-phase having similar trend, only phase B is selected as the test data, and the steady-state control chart output parameters are shown in the following table 1:

Table 1. A table with head.

| Substation Name | Output parameters |
|-----------------|-------------------|
|                 | UCL_\(\bar{X}\) | UCL_S | CL_\(R\) |
| Substation E    | 0.816             | 0.024  | 0.799    |
| Substation D    | 0.957             | 0.009  | 0.951    |
The time series data is used as input real-time data, and it is sequentially determined whether an abnormality occurs in each group (5 points), and the accumulated features including continuous abnormal time and the value of R are calculated. The final calculation result and Warning time is shown in the Table 2.

### Table 2. A table with head.

| Substation Name | Continuous abnormal time | R  | Warning time |
|-----------------|--------------------------|----|--------------|
| Substation E    | 04:35-05:12              | 1.12| no           |
| Substation E    | 05:13-06:27              | 1.15| no           |
| Substation E    | 11:56-17:01              | 3.03| 12:06        |
| Substation E    | 21:26-23:53              | 2.66| 21:36        |
| Substation D    | 04:36-06:22              | 1.06| no           |
| Substation D    | 11:55-14:21              | 1.94| 12:05        |
| Substation D    | 14:22-17:02              | 1.29| no           |
| Substation D    | 21:59-23:53              | 2.37| 22:09        |

According to Table 2, time segments in which the R value of substation E is greater than 1.8 are 11:56-17:01, 21:26-23:53, and the warning is given at 12:06 and 21:36. The time segments where the station R value is greater than 1.8 are 11:55-14:21, 21:59-23:53, and early warnings are given at 12:05 and 22:09. It can be seen that substation E and the substation D in the region have two harmonic amplification events on certain day. Meanwhile, checking the grid operation mode adjustment log, and found that the substation D has cut capacitors at 12:05 and 21:58, which supports the conclusion of this paper.

### 4. Conclusions

This paper proposes a method for online recognition of harmonic amplification based on statistical control chart. The harmonic amplification event has the characteristics of continuous, large amplitude increase, and the abnormality is identify based on the statistical control chart. The harmonic amplification event is detected online by extracting cumulative features such as continuous abnormal time and average increase ratio. The feasibility and accuracy of the method are verified by an example.

For the harmonic amplification detection method proposed in this paper, there are still some shortcomings, such as the failure to identify the direct cause of this harmonic amplification, and the harmonic excitation source is which disturbance source. The above is the next problem to be solved.

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