The New Method of Harmonic Detection in Microgrid Electric Vehicle Charging Stations Based on the Improved HHT

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***Abstract*—The appearance of microgrid solves the shortcomings of distributed generation and attracts the attention of the whole world. What's more, it has brought both opportunities and challenges for the development of electric vehicle charging stations. But due to the increasing use of electric vehicle chargers, the harmonic pollution of microgrid is becoming more and more serious, and it causes harm to both electric equipments and large power grid. Taking measures to govern the harmonic pollution is imperative, but before governance, the accurate and real-time detection of harmonic is indispensible. So this paper puts forward to use the improved HHT to detect the harmonics. The improved HHT combines the support vector regression machine and the mirror extension to improve the end effect of HHT and make the instantaneous frequency and amplitude become more meaningful. What's more, the improved HHT can accurately detect the starting and ending time of harmonic disturbances. Through the simulation results, it can be confirmed that this method is efficient and applicable for the harmonic detection in microgrid electric vehicle charging stations.**

***Index Terms*—empirical mode decomposition (EMD); end effect; electric vehicle (EV); harmonic detection; Hilbert-Huang Transform (HHT); Hilbert marginal spectrum; microgrid; support vector regression (SVR)**

I. INTRODUCTION

WITH the development of microgrid and the widespread use of power elements such as rectifying device, frequency conversion speeder device and power electronic equipments, the harmonic pollution is becoming more and more serious. The harmonic problem of microgrid has become a hot issue at home and abroad [1-5]. The accurate and real-time detection of harmonic is the basis of harmonic analysis, and it has very important practical significance for the operation of microgrid. Unfortunately, due to the influence of non-stationary, randomness, distribution and other factors, it is not an easy task to detect the harmonic accurately. At present, the harmonic detection methods mainly include the Fast Fourier Transform (FFT) and the Wavelet Transform (WT) [6-7]. For the integer harmonics, FFT can detect accurately; but for the non-integer harmonics, FFT may come up with errors. Although the utilization of window function and interpolation algorithm can alleviate the spectral leakage and fence effect effectively, but these two methods are all at the expense of reduction in frequency resolution. Wavelet transform has the characteristic of multi-resolution, it can observe the signal from coarse to fine. As long as the appropriate wavelet basis function is chosen, the wavelet transform has the excellent time-frequency local performance. However, the wavelet transform is a theory based on the expansion of basis function, the same problem with different basis functions may lead to different results, the selection of best basis function has no rule to follow, which largely depends on the designer's experience.

Hilbert-Huang Transform (HHT) is a new method proposed by Norden E. Huang et al in 1998, which is suitable for the analysis of nonlinear and non-stationary signal [8-11]. For harmonic analysis, HHT is based on the characteristics of signal and can realize the adaptive decomposition of harmonic. What's more, this time-frequency analysis method doesn't have the problem of selection of basis function, which can realize the automatic extraction of harmonics in microgrid. Nevertheless, there still exist many problems when using HHT to deal with signals. In which, the end effect problem is one of the most important and difficult one to solve. Therefore, this paper puts forward to use the improved HHT to detect the harmonics in electric vehicle charging stations, experiment results show that this method can greatly improve the end effect problem of HHT and achieve very good results.

II. THE BASIC PRINCIPLE OF HHT AND ITS END EFFECT PROBLEM

A. The basic principle of HHT

The HHT method is composed of empirical mode decomposition (EMD) and Hilbert transform (HT). Its core

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part is to decompose the signal through EMD method and get the intrinsic mode components (IMF) of signal; the detailed process of EMD is shown in Fig. 1. For the IMF components, they must satisfy the following two conditions: (1) the number of zero-crossing points and the number of extreme points must be equal or at most differ by one; (2) the mean value of the envelope defined by the local maxima and the envelop defined by the local minimum is zero. Once the IMF components are obtained, then do the Hilbert transform on them so as to obtain the instantaneous frequency and amplitude of signal.

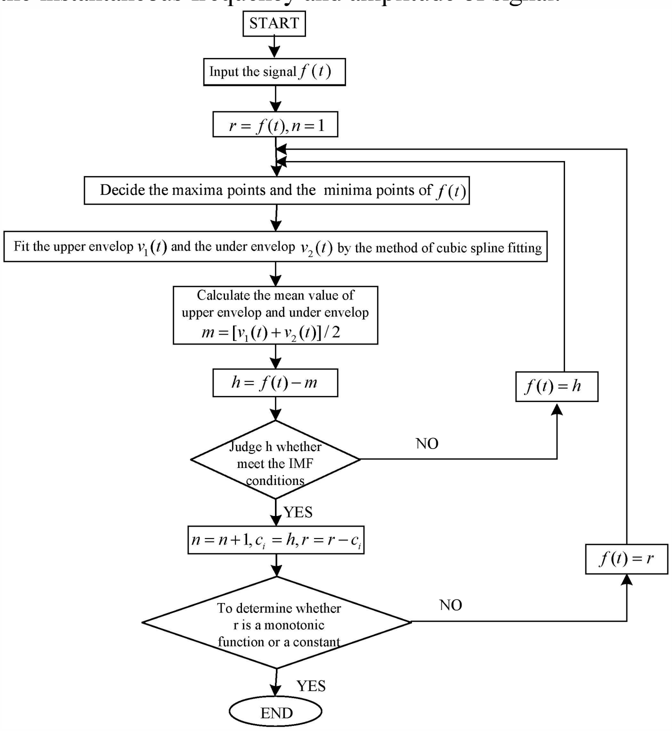


Fig. 1. The flowchart of empirical mode decomposition

Through the decomposition process mentioned in Fig. 1, the signal can be expressed as follows:

$$f(t) = \sum_{i=1}^{n} c_i(t) + r_n(t) \tag{1}$$

Do the Hilbert Transform on IMF component c_i :

$$H\left[c_i(t)\right] = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{c_i(\tau)}{t-\tau} d\tau \tag{2}$$

The analytic signal $x(t)$ can be built and shown in (3):

$$x(t) = c_i(t) + jH[c_i(t)] = a_i(t)e^{j\theta_i(t)} \tag{3}$$

In (3), $a_i(t)$ is the amplitude function; $\theta_i(t)$ is the phase function.

$$\begin{cases} a_i(t) = \sqrt{c_i(t)^2 + H[c_i(t)]^2} \\ \theta_i(t) = \arctan[H[c_i(t)]/c_i(t)] \end{cases} \tag{4}$$

Through the phase function $\theta_i(t)$, the instantaneous frequency of each IMF component can be obtained by (5).

$$f_i(t) = \frac{1}{2\pi}\frac{d\theta_i(t)}{dt} \tag{5}$$

B. The Hilbert marginal spectrum

According to (2), do the Hilbert transform on each IMF component and the signal $f(t)$ can also be expressed as follows:

$$f(t) = \mathrm{Re}\sum_{i=1}^{n} a_i(t)e^{j\theta_i(t)} \tag{6}$$

Here, the residue $r_n(t)$ has been left out on purpose, for it is either a monotonic function or a constant, and the expansion of (6) is called the Hilbert spectrum $H(\omega, t)$.

$$H(\omega, t) = \mathrm{Re}\sum_{i=1}^{n} a_i(t)e^{j\int \omega_i(t)dt} \tag{7}$$

With the Hilbert spectrum defined, then the Hilbert marginal spectrum can also be defined as follows:

$$h(\omega) = \int_0^T H(\omega, t)dt \tag{8}$$

In (8), T is the sampling time. The marginal spectrum offers a measure of the total amplitude contribution from each frequency value. This spectrum represents the accumulated amplitude over the entire data span in a probabilistic sense.

C. The end effect problem of HHT

For the end effect problem, it mainly shows in two respects [12-13]: (1) when using the EMD method to decompose the non-stationary signal, the both data ends will produce the divergence phenomenon. Along with the decomposition process, the divergence may pollute the inward data gradually, and the result will be distorted seriously; (2) when doing the Hilbert transform, the signal ends will also produce the serious end effect. If the end effect problem has not been suppressed effectively, the Hilbert spectrum can not reflect the characteristics of original signal. At present, the researchers have proposed some methods to inhibit the end effect, including the neural network extension method [12], extreme point extension method [13], AR model extension method [14], support vector regression machine extension method [15] and mirror extension method [16]; these methods have achieved certain results in the end effect inhibition. However, the mirror extension method generally requires that the mirror should be put on the extreme point, if the endpoint is not an extreme point, it is necessary to amputate part data in order to place the mirror on the extreme point. When dealing with a short data, it may influence the processing effect to a certain extent; the AR model can only suitable for the stationary and simple non-stationary data; neural network has the inherent defects of over learning, local minimum as well as the network structure unduly depends on the experience; all of these restrict them from solving the end effect problem effectively.

III. THE SOLUTION OF END EFFECT PROBLEM IN IMPROVED HHT

The support vector regression (SVR) is a machine learning technique based on the structural risk minimization principle. This method has good generalization performance and accuracy, its appearance overcomes the shortcomings of extension methods mentioned above and obtains good results in the data sequence prediction. However, when the predicted data is excessive, the SVR may cause bigger error. Therefore, this paper proposes to use the support vector regression machine and the mirror extension method to extend the data, the combination of this two methods not only avoids the drawbacks of SVR but also overcomes the defects of mirror extension method, which effectively improves the end effect of HHT.

At present, the mirror extension method has been widely used in data extension, Huang Da-ji and other scholars have already made a detailed description on it, specific extension process can refer to [16-17]. In the following part, this paper mainly focuses on the support vector regression method.

Before data extension, it is necessary to construct a model of support vector regression. The model is shown in (9), in which, a_i and a_i^* is the nonnegative Lagrange multiplier; b is the bias term; $k(x_i, y_i)$ is the kernel function.

$$f(x) = \sum_{i=1}^{l} \left(\overline{a_i}^* - \overline{a_i} \right) k(x_i, y_i) + \overline{b} \tag{9}$$

For a given data sequence $s(1)$, $s(2)$, $\cdots$ $s(N)$, in which N is the number of sampling point. Then do the leftward and rightward extension on data based on the support vector regression model. Here, take the rightward extension as an example: firstly, determine the number of extended points m and the training samples l. Then form the training sample set T according to certain rules. In the training sample set T, $x_i = [s(i), s(i+1), \ldots, s(N-l+i-1)]^T$, $y_i = s(N-l+i)$, $T = \{(x_1, y_1), (x_2, y_2), \ldots, (x_l, y_l)\}$, $1 \le i \le l$. Through the regression model, the first predicted data $s(N+1)$ can be obtained:

$$s(N+1) = \sum_{i=1}^{l} \left(\overline{a_i}^* - \overline{a_i} \right) k(x_i, x_{l+1}) + \overline{b} \tag{10}$$

In (10), $x_{l+1} = [s(l+1), s(l+2), \ldots, s(N)]^T$. Take the $s(N+1)$ as the new boundary point of original data sequence, then the next predicted point can be obtained. In the same way, according to the number of extended data, all of the extended sequence can be got. For any predicted data, it can be expressed by (11):

$$s(N+n) = \sum_{i=1}^{l} \left(\overline{a_i}^* - \overline{a_i} \right) k(x_i, x_{l+n}) + \overline{b} \tag{11}$$

In (11), $x_{l+n} = [s(l+n), s(l+n+1), \ldots, s(N+n-1)]^T$, $1 \le n \le m$.

IV. The Application of Improved HHT in Microgrid Harmonic Detection

The simple schematic diagram of microgrid is shown in Fig. 2. From Fig. 2, it can be seen clearly that electric vehicle charging stations should rely on the inverters to connect to the microsources. However, the existence of inverters and nonlinear loads will result in the generation of harmonics; the harmonic current and voltage are a kind of pollution to the public grid [18]. Therefore, this paper proposes to use the improved HHT to detect the harmonic which is generated by EV chargers in microgrid. For the harmonic signal S, according to the detection method mentioned above, the signal can be handled as follows:

1) Firstly, use the support vector regression to extend a signal segment at each end of the original harmonic signal S, and the signal S_1 can be obtained. For each signal segment, it must contain a maximum point and a minimum point;

2) For the signal S_1 derived from step one, use the mirror extension method to map the signal outward and a periodic signal S_2 is obtained, which is two times the length of S_1;

3) Then use the EMD method to decompose the signal S_2 and get a series of IMF components;

4) Do the Hilbert transform on each IMF component, and the instantaneous frequency and amplitude of it can be obtained. Finally, get rid of the extended portion of the data, the final result is obtained.

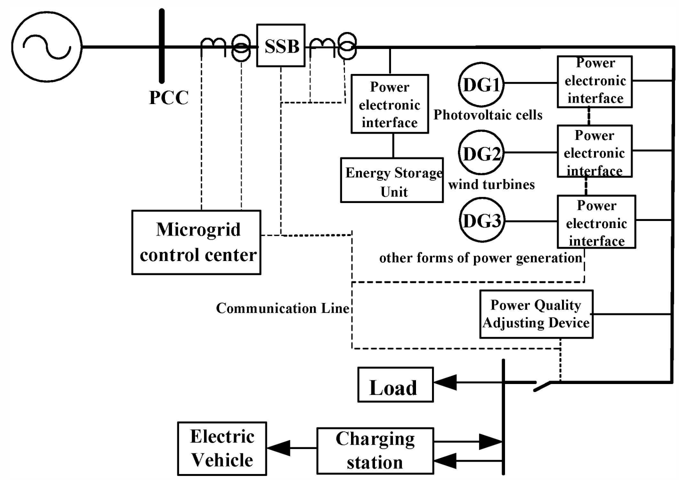


Fig. 2 The simple schematic diagram of microgrid

V. Simulation Verification and Analysis

A. Example 1

In order to verify the effectiveness of improved HHT in solving the end effect problem, now take the short-time harmonic signal as an example, the waveform of harmonic current is shown in Fig. 3 and the expression is shown in (12):

$$x(t) = \sum_{i=1}^{3} A_i \cos(2 * pi * f_i * t) \tag{12}$$

In which, $A_1 = 3A$, $A_2 = 2A$, $A_3 = 1.5A$; $f_1 = 4Hz$, $f_2 = 2Hz$, $f_3 = 0.5Hz$. The sampling frequency f_s is $300Hz$。

Fit the upper envelop and under envelop of short-time harmonic signal by using the cubic spline interpolation, the waveform of envelops are shown in Fig. 4. As can be seen from Fig. 4, the original signal only has three maxima points and four minima points. Because it cannot be determined whether the endpoint is an extreme point or not, the trend of envelope is not known and the envelopes may not contain all the data. Thus, it will produce serious distortion and end effect problem. At the same time, as the data sequence is very short, the end effect may "pollute" the inward data gradually with the process of empirical mode decomposition. Fig. 5 is the comparison diagram of direct EMD results and the original IMF components. By comparison, it can be found that the decomposition results all come up with serious deviation. So before using the EMD method, it is necessary to restrain the end effect problem, otherwise the decomposition results may become meaningless.

In order to improve the end effect problem generated by EMD process, this paper proposed to use the support vector regression machine and mirror extension method to extend the harmonic sequence. When using the SVR, the selection of parameters are as follows: penalty parameter C is ∞, precision parameter ε is 0, loss function is the linear insensitive loss function, kernel function is the linear kernel function, the number of training samples is 100, and the training sample set T is $\{(x_1,y_1),(x_2,y_2),\ldots,(x_{100},y_{100})\}$. According to the regression model shown in (9), extend 100 points on both signal ends respectively. Then its EMD results can be obtained and shown in Fig. 6. From Fig. 6, it can be seen clearly that the EMD results derived from improved HHT come to be coincident with original IMF components. Compared with direct EMD results, the waveform of IMF components have been improved greatly. Especially for IMF3, its direct EMD results is only a straight line, when using the improved HHT to deal with it, although there are still some errors, the treatment effect is quite satisfactory. Therefore, the improved HHT method is efficient in solving the end effect problem of original HHT method.

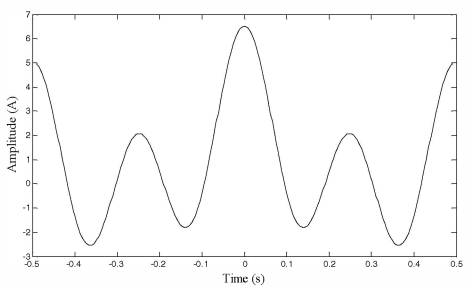


Fig. 3 The waveform of short-time harmonic current

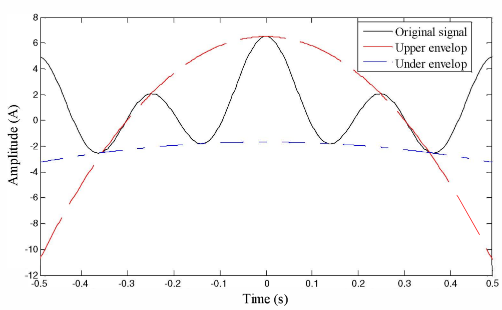
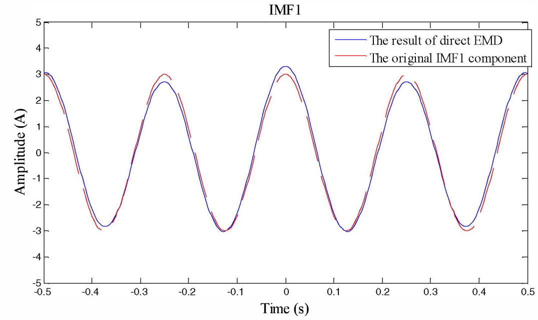
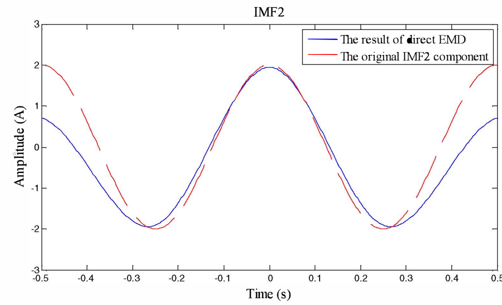


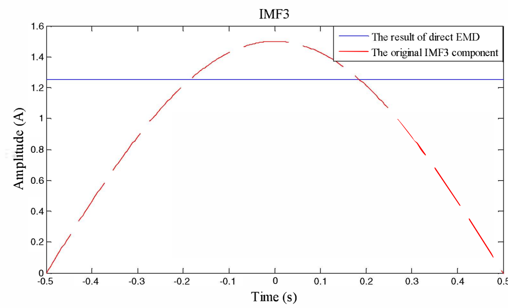
Fig. 4 The envelop of short-time harmonic signal



a. IMF1

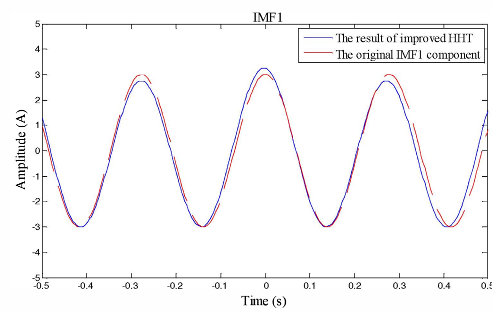


b. IMF2

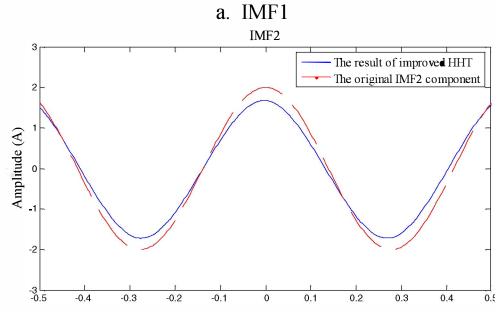


c. IMF3

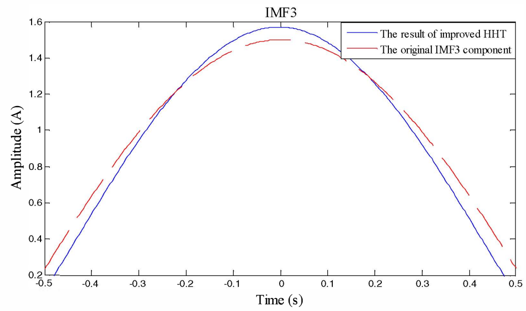
Fig. 5 The results of direct EMD



a. IMF1



b. IMF2



c. IMF3

Fig. 6 The results of improved HHT

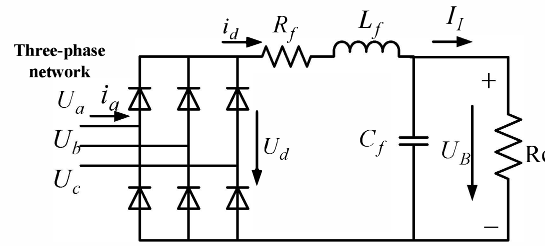


Fig. 8. The principle diagram of Charger

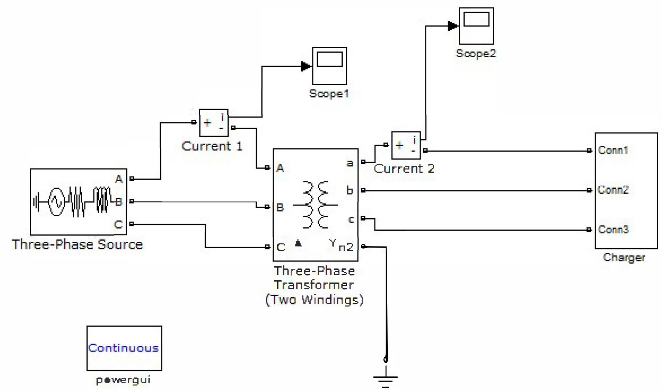


Fig. 9. The simulation model of charging station

B. Example 2

From *Example* 1, it can be known that improved HHT well solves the end effect problem of original HHT. Now apply this method to detect the harmonics that generated by EV chargers. Fig. 7 is the schematic diagram of high frequency charger. In this paper, Matlab/Simulink is chosen as the research platform. While using the Matlab, it is a relatively complex task to build the model of high frequency charger, and the amount of computation is large, what's more, it can be difficult to observe the variation of current during the charging process. So this paper replaces the equivalent input impedance of high-frequency power conversion circuit with a nonlinear resistance R_c approximately and the expression of R_c is shown in (13).

$$R_C = \frac{U_B}{I_I} = \frac{\eta U_B{}^2}{P_0} = \frac{\eta U_B{}^2}{U_0 I_0} \tag{13}$$

In which, P_0 is for the output power of charger, η is for the charging efficiency. Based on the principle diagram of charger which is shown in Fig. 8, a simulation model of charging station is built and shown in Fig. 9. Then the waveform of harmonic current can be obtained and shown in Fig. 10.

Use the support vector regression and mirror extension to extend the harmonic signal, when doing the SVR extension, the selection of parameters are the same with example 1. Then decompose the extended harmonic signal with EMD method and do the Hilbert transform on each IMF components, the instantaneous frequency and amplitude of each IMF components are shown in Fig. 11 and Fig. 12, respectively.The simulation result shows that the order of harmonic currents is $6k \pm 1$, and there exist clear inverse proportions between the amplitude of harmonics and the harmonic orders, the higher harmonic order is, the lower harmonic amplitude will be.

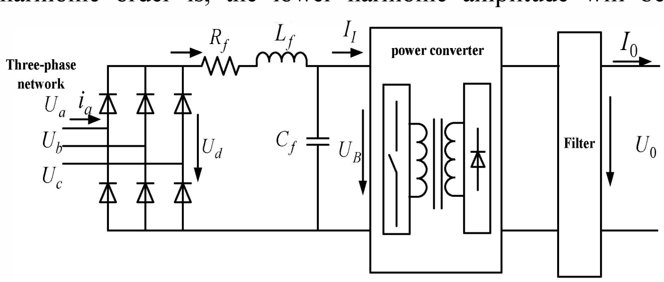


Fig. 7. The schematic diagram of high frequency charger

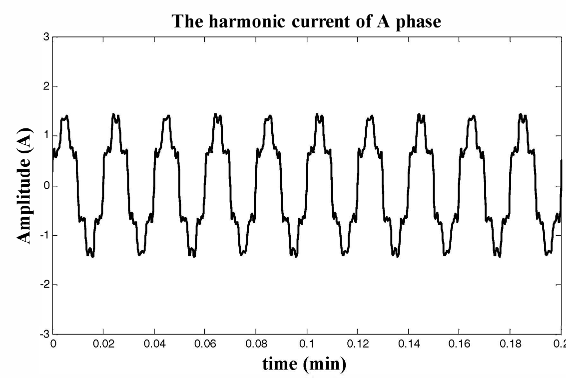


Fig. 10 The harmonic current of electric vehicle charging stations

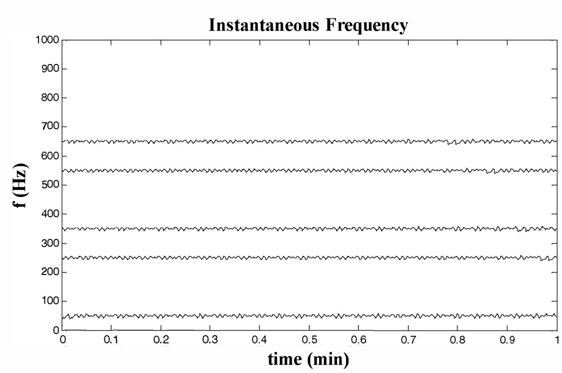


Fig. 11 The instantaneous frequency of harmonics

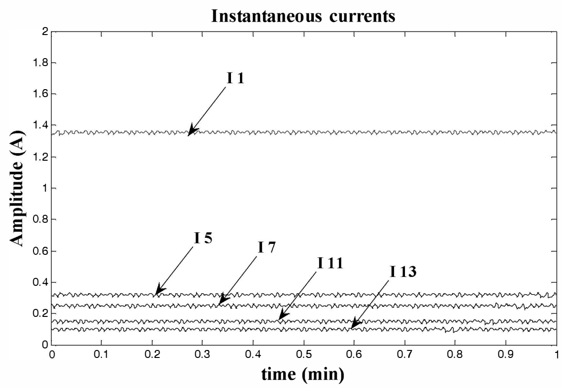


Fig. 12 The instantaneous amplitude of harmonics

VI. CONCLUSION

The disturbance generated by microgrid harmonic has already caused the extensive concern in the world. With the widespread use of electric vehicles, its advantages such as environmentally friendly and energy-saving have made it gain increasing popularity all over the world, but the harmonic currents that generated in the process of charging have serious impact on the power quality of microgrid. Therefore, this paper proposes to use the improved HHT method to detect the harmonic generated by EV charging stations. The improved HHT combines the support vector regression machine and the mirror extension method to solve the end effect problem of original HHT, and the SVR doesn't overly depend on the selection of parameters, the same parameters for different examples all achieved very good results. Through using this method, the instantaneous frequency and amplitude of harmonics are obtained. The results show that this method can not only help to get the meaningful instantaneous frequency and amplitude from harmonics, but also lay a solid theoretical basis for the microgrid harmonic analysis.

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