Voltage Harmonic and Interharmonic Detection Method for DC Microgrid based on Hanning Window Interpolation

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Abstract. With the development of power electronics technology and the increasing DC sensitive load, DC microgrid is an important direction for future power distribution. At present, there are few studies on the power quality of DC microgrids. This paper introduces a DC voltage harmonic and interharmonic detection method suitable for DC microgrid. The voltage of the DC microgrid is divided into DC voltage and harmonics and interharmonics, and they are studied separately. For the DC voltage, use the regression equation to represent and restore it. For harmonics and interharmonics, the method of windowed Fourier transform is used for analysis, and the quadratic interpolation method is used for correction. Through simulation, the detection and reduction of DC voltage harmonics and interharmonics under various operating conditions are analyzed. Finally, the feasibility and accuracy of this algorithm are verified.

1. Introduction

In the past more than a century, the AC system has dominated the power supply with its advantages of convenient transmission and easy arc extinguishing[1]. The DC microgrid has the characteristics of facilitating the access and use of the distributed power source, facilitating the access of the DC load, and the transmission power of the line is larger than the AC. In recent years, with the large-scale application of fully-controlled power electronic devices and the rapid development of distributed power sources, solving some problems of the existing distribution network by DC micro-network will also become a new trend of power grid development.

At present, most researches on DC microgrids focus on topological structures [2], voltage levels, control methods [3] and key technologies such as inverters [4]. Generally on the DC microgrid, there is not much research on power quality[5,6], especially for DC microgrid’s voltage harmonics.

Due to the difference between DC and AC system, the detection method of the power quality in the AC system is not necessarily adapted in the DC microgrid. Therefore, a new detection method is needed for the DC microgrid. Accurate measurement of harmonics and interharmonics provides a basis for the estimation and control of harmonics and interharmonics in DC microgrids, which is of great significance. Nowadays, domestic and foreign scholars have studied the harmonics and interharmonics of AC systems more maturely[7]. The WFT can overcome the defect that FFT does not have local analysis ability to some extent, so it is widely used in the detection and analysis of harmonics[8]. The combined WFT and interpolation algorithm have achieved good results.
This paper designs a detection algorithm that can detect DC microgrid’s voltage based on Hanning window double line interpolation method. Using the regression curve to represent the DC voltage of the microgrid, DC voltage detection and separation can be achieved. The AC part is analyzed by WFT using Hanning window, and then a DC microgrid’s voltage harmonic and interharmonic detection algorithm is proposed. Finally, the feasibility and accuracy of the algorithm are verified by Matlab.

2. DC voltage detection method based on Hanning window WFT and interpolation algorithm

The Fourier series can directly observe the amplitude-frequency characteristics of each harmonic in the electrical signal, so it is the most widely used in harmonic detection. The expression is:

\[
F(\omega) = \tilde{f}(\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t} dt
\]  

(1)

In practical applications, fast Fourier transform is prone to fence effect, leakage effect and aliasing effect[9]. Usually, a combination of WFT and spectral interpolation is used. This method not only can obtain accurate frequency, amplitude and phase, but also has good time domain analysis capability.

WFT is in the framework of Fourier transform, which regards the non-stationary process as a superposition of a series of short-term stationary signals, while the short-term is to cover the whole area by the translation of a parameter \( \tau \). A window function \( g(t-\tau) \) is used to multiply the signal \( f(t) \) to achieve windowing and translation near \( \tau \), and then Fourier transform. The expression is:

\[
G_{f}(\omega, \tau) = \int_{-\infty}^{\infty} f(t)g(t-\tau)e^{-j\omega t} dt = \int_{-\infty}^{\infty} f(t)\tilde{g}(\omega, \tau)(t)dt
\]  

(2)

The Hanning window function is a cosine window function, which not only has a small amount of calculation, but also reduces the leakage between harmonics by adjusting the sampling length. Therefore, this paper chooses Hanning window as the window function.

In the sampling spectrogram of the signal sample after the FFT transform, it is possible to miss the key peak point, and the resulting error is called the fence effect[10].

In Figure 1, \( k_0 \) is the theoretical sampling point, that is, the peak position, \( k_1 \) and \( k_2 \) are actual sampling points, and \( |Y(k)| \) is the respective amplitude. For the fence effect, the peak point is generally corrected by spectral line interpolation, and the theoretical sample value is estimated by selecting several sampling points near the peak. In this paper, we consider the double line interpolation method by considering the accuracy and calculation amount. Let \( |Y(k_{\text{max}})|, |Y(k_{\text{min}})| \) be the larger and smaller of \( |Y(k_1)|, |Y(k_2)| \). So:

\[
\beta = \frac{|Y(k_{\text{max}})|}{|Y(k_{\text{min}})|}, \quad \delta = \frac{2\beta - 1}{\beta + 1}
\]  

(3)

(4)

The frequency, amplitude, and phase correction formulas are:  

\[
f_s = (k_1 - 1 + \delta) \cdot f_{\text{min}} \quad (f_{\text{min}} = k_2 - k_1)
\]  

(5)
The harmonic, the number of harmonics, and $f_{\text{min}}$ is the lowest resolution of the FFT. 

The DC microgrid’s voltage consists of DC voltage and harmonics and interharmonics.

$$U(t) = U_{dc}(t) + \sum_{h} U_{h} \cos(2\pi ft + \theta_{h})$$  \hspace{1cm} (8)

In equation (8), $U_{dc}$ is the DC portion of the voltage time-varying, $U_{h}$ is the amplitude of the harmonics and interharmonics, $h$ is the harmonic, the number of harmonics, and $\theta_{h}$ is the beginning phase angle of the $h_{th}$ harmonic and interharmonics.

First, the method filters the DC voltage to obtain voltage harmonics and interharmonics of the microgrid’s voltage. Secondly, it performs WFT and quadratic interpolation correction to obtain more accurate harmonic, interharmonic frequency, amplitude and phase. Then, by adding harmonics and interharmonics of these different frequencies, the AC component in the DC microgrid’s voltage can be restored. Finally, the AC component is added to the DC voltage to obtain the original DC microgrid voltage with relatively accurate reduction.

3. DC voltage detection and calculation
The majority of the AC microgrid’s voltage is the power frequency AC voltage. In contrast, most of the DC microgrid’s voltage is DC voltage, and harmonics and interharmonics as AC part are only a small part. At the same time, the microgrid’s voltage is not a constant ideal value, and the microgrid’s voltage is different at different times. Accurate separation and detection of DC voltage in DC microgrid’s voltage is an important prerequisite for detecting harmonics and interharmonics in voltage.

In this paper, the regression equation based on polynomial is used to fit the DC voltage of the microgrid voltage. The regression equation reflects the regression relationship of dependent variable to independent variable obtained by regression analysis based on sample data. The regression equation of the AC function is the x-axis. At this point, the discrete function values in each cycle can be considered as special residuals of the regular distribution around the regression equation. Similarly, the alternating voltages of harmonics and interharmonics in the DC microgrid can be approximated as special residuals around the DC voltage. Regression curves can be obtained by establishing equations to reduce the effects of these “residuals”. Therefore, the regression curve can also be approximated as a DC voltage expression after the AC component is eliminated.

In the voltage curve, the time $t$ is the independent variable of the function, and the voltage value $U_{dc}$ is the dependent variable of the function. The time and voltage DC components can be approximated as:

$$U_{dc}(t) \approx BT = b_0 + b_1 t + b_2 t^2 + \cdots + b_n t^n$$  \hspace{1cm} (9)

The normal equations for this function are

$$\begin{align*}
b_0 &+ b_1 \sum_{i=1}^{N} t_i + \cdots + b_N \sum_{i=1}^{N} t_i^n = \sum_{i=1}^{N} u_i \approx \sum_{i=1}^{N} u_{dc_i} \\
N b_0 \sum_{i=1}^{N} t_i + b_1 \sum_{i=1}^{N} t_i^2 + \cdots + b_N \sum_{i=1}^{N} t_i^{n+1} &\approx \sum_{i=1}^{N} t_i u_i \approx \sum_{i=1}^{N} t_i u_{dc_i} \\
N b_0 \sum_{i=1}^{N} t_i^n + b_1 \sum_{i=1}^{N} t_i^{n+1} + \cdots + b_N \sum_{i=1}^{N} t_i^{2n} &\approx \sum_{i=1}^{N} t_i^n u_i \approx \sum_{i=1}^{N} t_i^n u_{dc_i}
\end{align*}$$  \hspace{1cm} (10)

The normal equations matrix form of this function is
\[
\begin{pmatrix}
\sum_{i=1}^{N} \sum_{j=1}^{N} t_{ij} & \ldots & \sum_{i=1}^{N} t_{in} \\
\sum_{i=1}^{N} \sum_{j=1}^{N} t_{ij}^2 & \ldots & \sum_{i=1}^{N} t_{ij}^{n+1} \\
\sum_{i=1}^{N} \sum_{j=1}^{N} t_{ij}^{n+1} & \ldots & \sum_{i=1}^{N} t_{ij}^{2n}
\end{pmatrix}
\begin{pmatrix}
b_0 \\
\vdots \\
b_n
\end{pmatrix}
=\begin{pmatrix}
\sum_{i=1}^{N} u_i \\
\sum_{i=1}^{N} \sum_{j=1}^{N} u_{ij} t_{ij} \\
\sum_{i=1}^{N} \sum_{j=1}^{N} u_{ij}^2 \\
\sum_{i=1}^{N} \sum_{j=1}^{N} u_{ij}^{n+1} \\
\sum_{i=1}^{N} \sum_{j=1}^{N} u_{ij}^{n+1}
\end{pmatrix}
\begin{pmatrix}
1 \\
t \\
t^2 \\
t^n
\end{pmatrix}
\]

(11)

Let the first square matrix for \( t \) be \( T \), the coefficient matrix be \( B \), the matrix for \( t \) and \( u \), and the matrix for \( t \) and \( u_{dc} \) be \( U \) and \( U_1 \) respectively, then the above matrix can be abbreviated as:

\[
TB = U \approx U_1
\]

(12)

Further, the voltage DC component \( u_{dc} \) is obtained:

\[
u_{dc} \approx B^T T_i = (T^{-1} U)^T T_i = (b_0 \ b_1 \ \ldots \ b_n) \times \begin{pmatrix} 1 \\ t \\ t^2 \\ \vdots \\ t^n \end{pmatrix}
\]

(13)

The voltage change is not severe within 0.05 s, and the one-fourth equation can accurately describe the change of the DC component, which is

\[
u_{dc} = b_0 + b_1 t + b_2 t^2 + b_3 t^3 + b_4 t^4
\]

(14)

Through the obtained \( u_{dc}(t) \) curve, not only harmonics can be detected and analyzed, but also other power quality phenomena such as voltage fluctuation and voltage sag can be analyzed.

4. Simulation analysis

In this paper, the DC microgrid’s voltage is detected by establishing a simulation model with a DC bus of 1KV. Since the DC microgrid doesn’t have problems such as reactive power and phase, the active imbalance is the root cause of the DC microgrid voltage deviation. Therefore, when using the MATLAB/SIMULINK software to simulate this microgrid, by setting different active power outputs, to get the real-time voltage on the DC bus under different working conditions, and carry out harmonic detection and analysis.

4.1. Voltage harmonic detection at steady state

When the system is running stably, the distributed power supply and AC power output are relatively stable, and the load is relatively stable. At this time, the power is balanced, the output power is equal to the input power, and the voltage is relatively stable.

Taking the voltage of 7.5s–7.55s as an example, the method is applied to analyze the DC voltage and harmonic content. The WFT spectrum and the resulting DC voltage are shown in the figure 2 and 3.
The DC voltage expression is:

\[ U_{dc}(t) = 1001.4 - 501.9(t - 7.5) + 25371(t - 7.5)^2 - 4.1 \times 10^5(t - 7.5)^3 + 1.3 \times 10^6(t - 7.5)^4 \]  \hspace{1cm} (15)

The AC component is shown in the table 1 below.

| Frequency(Hz) | Amplitude(V) |
|---------------|--------------|
| 299.993       | 6.145        |
| 600.001       | 0.825        |
| 900.043       | 0.205        |
| 999.996       | 29.229       |
| 1199.986      | 0.010        |
| 1999.996      | 12.385       |
| 2999.995      | 6.118        |

The frequency with large harmonic amplitude is mainly 1000*kHz harmonic and 6k harmonic of power frequency 50Hz, which indicates that the system harmonics from the stable operation of DC microgrid mainly from the switching frequency of rectifiers and other power electronic control devices.

4.2. Voltage harmonic detection during fluctuations

The imbalance between the system output power and the input power will cause the DC microgrid voltage to vary greatly. For example, when the illumination changes, it will cause the distributed power output to change [11]. The change in illumination and the resulting voltage fluctuations of the DC bus are shown in the figure 4and 5 below.

Taking the voltage of 2.5s~2.55s as an example, the method is applied to analyze the DC voltage and harmonic content. The WFT spectrum and the resulting DC voltage are shown in the figure 6and 7.
The DC voltage expression is:

\[ U_{dc}(t) = 995.4 + 354(t - 2.5) - 7.3 \times 10^3(t - 2.5)^2 + 2.3 \times 10^6(t - 2.5)^3 - 2.2 \times 10^7(t - 2.5)^4 \]  

(16)

The AC component is shown in the table 2 below.

Table 2. AC component

| Frequency(\(\text{Hz}\)) | Amplitude(\(\text{V}\)) |
|-------------------------|-------------------------|
| 299.533                | 2.421                   |
| 599.530                | 0.371                   |
| 899.438                | 0.083                   |
| 999.906                | 12.376                  |
| 1199.728               | 0.037                   |
| 1999.964               | 5.267                   |
| 3000.030               | 2.613                   |

The content of harmonic amplitude is mainly 1000*kHz harmonic and 6k harmonic of power frequency 50Hz, which indicates that the system harmonics of DC microgrid power fluctuation also depend on the switching frequency of rectifier and other power electronic devices.

4.3. Voltage interharmonic detection

The system only contains harmonics In the above two cases. In order to verify that the algorithm's measurement of interharmonics is equally accurate, 120Hz interharmonics are injected into the AC grid. When the AC system contains interharmonics, they are transmitted to the DC bus through the rectifier. Taking the voltage of 7.7s~7.75s as an example, the method is applied to analyze the DC voltage and harmonic content. The WFT spectrum and the resulting DC voltage are shown in the figure 8 and 9:

The DC voltage expression is:

\[ U_{dc}(t) = 1009 - 2487(t - 7.7) + 1.4 \times 10^4(t - 7.7)^2 - 2.8 \times 10^6(t - 7.7)^3 + 1.7 \times 10^7(t - 7.7)^4 \]  

(17)

The AC component is shown in the table 3 below.

Table 3. AC component

| Frequency(\(\text{Hz}\)) | Amplitude(\(\text{V}\)) |
|-------------------------|-------------------------|
| 16.523                  | 2.936                   |
| 70.334                  | 16.431                  |
| 300.027                 | 6.120                   |
| 600.020                 | 0.815                   |
| 999.997                 | 29.225                  |
It can be seen from the table that at this time, not only the harmonic content but also a large amount of interharmonic components are detected in the DC microgrid. It shows that this method has a good effect on the detection of interharmonics.

5. Conclusion
In this paper, a DC harmonic and interharmonic detection method suitable for DC microgrid is proposed. The proposed detection method fully considers the time-varying of the DC microgrid voltage, and detects the DC voltage and the AC content separately. The DC voltage is expressed by a one-element fourth-order equation. The communication part draws on the mature detection method of the AC system, firstly through the WFT, and then through the quadratic interpolation correction to obtain the amplitude and frequency of harmonics and interharmonics. Thereby, all the data of the DC microgrid voltage is obtained.

The simulation example shows that the proposed method has higher accuracy under different working conditions, which verifies the feasibility and effectiveness of the algorithm. The detection method in this paper provides a practical method for the detection of DC microgrid voltage. At the same time, it laid the foundation for the evaluation and improvement of DC microgrid voltage quality.

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