RESEARCH ON THE INTELLIGENT RECONSTRUCTION METHOD OF HARMONIC SIGNAL UNDER MULTI-OBJECTIVE FAULT INTERFERENCE

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Abstract: At present, most of the research on the intelligent reconstruction of harmonic signal of power grid focuses on the reconstruction of signal. However, many signal processing does not require accurate signal reconstruction. For example, in the problem of harmonic reconstruction of the power grid, if the harmonic signal of the power grid can be detected directly from the intelligent reconstruction data, there is no need to reconstruct the original harmonic signal. In order to use the network harmonic signal reconstruction algorithm to directly extract the required characteristic quantity from the sampling value to complete the signal detection task. Therefore, the research on the intelligent reconstruction method of harmonic signal under multi-objective fault interference is proposed. The sparse degree and reconstruction matrix of harmonic signals of the power grid are determined through the intelligent reconstruction framework of harmonic signals of the power grid, and an algorithm for the reconstruction of harmonic signals of the power grid is proposed to realize the reconstruction of harmonic signals of the power grid. Simulation results show that this method has high precision in detecting harmonic signal and high precision in detecting harmonic signal.

1. Introduction
With the increasing load of power grid and the application of a large number of nonlinear devices, the problem of power grid harmonic is becoming more and more complicated. There are not only integer harmonics but also non-integer harmonics in power system. The traditional harmonic reconstruction method can detect the integer harmonics accurately, but the detection error of non-integer harmonics is large. Wavelet transform can be used for non-stationary harmonic detection, but because of the crossover phenomenon between frequency bands, the selection of wavelet basis is difficult and the detection accuracy is affected. The harmonic intelligent reconstruction methods of power grid have their own characteristics and application limitations, but they are all based on the traditional signal processing sampling theorem, that is, the collected power grid signals must strictly abide by the sampling frequency, which must be more than twice the highest frequency of power grid signals. Therefore, this paper studies the intelligent reconstruction method of power grid harmonic signal under multi-objective fault interference to promote the development of national economy.
2. The intelligent reconstruction method of harmonic signal in multi-objective fault interference

2.1. A framework for intelligent reconstruction of harmonic signals in power grids

Sampling theorem, also known as Shannon's sampling law or Nyquist's sampling law, is the cornerstone of harmonic signal processing in power networks and the law followed in the process of sampling band limited signals. The sampling theorem was first proposed by American telecom engineer H. Nyquist in 1928, so it is called Nyquist sampling theorem. 1948, founder of information theory C. E. Shannon explicitly stated this theorem and formally cited it as a theorem, so it is also known as Shannon sampling theorem in many literatures. The sampling theorem states that if the bandwidth of the harmonic signal of the grid is less than the Nyquist frequency (that is, half of the sampling frequency), then the discrete sampling points can fully represent the original signal, and the frequency signals above or at the Nyquist frequency will lead to aliasing. Most applications require that aliasing be avoided, and the severity of the problem depends on the relative strength of these aliased frequency signals. In other words, the sampling theorem requires that the sampling rate of the harmonic signal of the power grid should be twice higher than the bandwidth of the harmonic signal of the power grid, so that the harmonic signal of the power grid can be perfectly reconstructed[1].

Obviously, this process, which takes sampling theorem as criterion, wastes a lot of sampling resources. This leads naturally to the following questions:

1) can the frequency sampling signal far below the sampling theorem be used to ensure no loss of information?

2) can the sampling of harmonic signals of the power grid be transformed into the sampling of information?

If this problem is solved, the sampling frequency and processing time of harmonic signal can be greatly reduced, and the time and space loss of data storage and transmission can be reduced. This seems impossible, because the reconstructed harmonic signal data of the grid is not a subset of the reconstructed harmonic signal data of the grid. In this way, only a small part of the incomplete data in the harmonic signal of the power grid can be collected. Some information is lost forever and cannot be recovered.

The best way to obtain information is to design a reasonable way to obtain information, so as to obtain as much information as possible with as little reconstructed data as possible. If you expect to collect a few power grid harmonic signal data from a small amount of data can resolve the original harmonic signals of the global information grid, you need to ensure that the acquisition of a small amount of power grid harmonic signal data contains the global information of original signal, and the existing effective algorithm can from a small amount of reduction in power grid harmonic signal data out of the original signal.

Multi-objective fault[2] interferences no longer require the bandwidth of the harmonic signals of the power grid, but sparsity. The harmonic signals satisfying the conditions can be accurately reconstructed under the condition of less than Shannon sampling rate. This framework has become one of the research hotspots in the field of mathematics and engineering application, and has been highly concerned in the fields of information theory, medical imaging, image processing, radar imaging, pattern recognition and communication, etc.[3].

The idea of intelligent reconstruction based on multi-objective interference is to replace the full value of harmonic signal with a small number of non-adaptive sampling values, and combine the traditional data collection and data reconstruction into one, without the need of complex data coding algorithm. The research involves two aspects, sampling and reconstruction. The framework for intelligent reconstruction of power grid harmonic signals is shown in figure 1.

![Figure 1. A framework for intelligent reconstruction of harmonic signals in power grids](image-url)
2.2 Sparse representation of harmonic signals in a power network

The sparse representation problem of signals is how to find some orthogonal basis or tight framework \( \Psi \) and represent the original signal with as few basis functions as possible\cite{4} under this transformation basis. If you have a one dimensional finite length signal you can represent it as an \( N \times 1 \) vector in \( \mathbb{R}^N \), which is

\[
\begin{bmatrix}
f_1 \\
f_2 \\
\vdots \\
f_N 
\end{bmatrix} \in \mathbb{R}^N.
\]

According to reconstruction analysis theory, any grid harmonic signal in \( \mathbb{R}^N \) space can be represented by a linear combination of \( N \times 1 \) wiki function

\[
\begin{bmatrix}
f_1 \\
f_2 \\
\vdots \\
f_N 
\end{bmatrix} = \Phi f.
\]

Let's say that \( \Phi \) is an orthonormal basis, \( \Psi = [\Psi_1, \Psi_2, \ldots, \Psi_N] \). Then, under the orthogonal basis \( \Psi \), the power grid harmonic signal \( f \in \mathbb{R}^N \) can be expressed as:

\[
 f = \Psi x \quad \text{or} \quad f = \sum_{i=1}^{N} x_i \Psi_i
\]

Obviously, \( f \) and \( x \) are two equivalent representations of the harmonic signals in different domains, \( f \) in the time domain or space domain, and \( x \) in the \( \Psi \) domain. When the grid harmonic signal \( f \) can be expressed linearly by \( K \) basis functions, then \( f \) is sparse of \( K \). That is, the coefficient values of only \( K \) \( x_i \) in the above equation are non-zero, and the other \( N-K \) coefficient values are zero. If there are a small number of large coefficient values and a large number of small coefficient values in the above formula, the harmonic signal of the power network can be reconstructed. When the power grid harmonic signal \( f \in \mathbb{R}^N \) under some orthogonal basis or tight frame \( \Psi \) is reconfigurable, \( x \) for power grid harmonic signal sparse representation in domain \( \Psi \).f.

According to the above definition, the power grid harmonic signal is not sparse in the time domain, but it may become sparse through some transformation domain\cite{5}.

In general, the traditional reconstruction process refers to the approximation of the original signal by \( K \) large coefficients expanded on some orthogonal basis \( \Psi \). Determine \( K \) large coefficient positions in the transformation domain, throw away \( n-K \) small coefficients, and then encode \( K \) large coefficient positions and values, so as to achieve the purpose of compression. The reconstruction process is to put the \( K \) components back to the corresponding position, fill in 0 at other positions, construct the inverse \( \Psi^{-1} \) of orthogonal basis \( \Psi \), and reconstruct the original signal by inverse transformation\cite{6}.

It is possible to solve the above problems if we can overcome the traditional framework of sampling and reconstruction, and combine sampling and reconstruction into one. The combination of sparse transform and perceptive measurement matrix is one of the core components of harmonic signal in power network.

2.3 Determine the reconstruction matrix

If \( f \in \mathbb{R}^N \) is the reconstruction of signal, show that the signal in a transformation matrix \( \Psi \) can represent sparse to \( f = \Psi x \), thus further design grid harmonic signal reconstruction. This section focuses on the reconstruction matrix. Upfront design a dimension for the matrix phi \( M \times N \) (\( N \) is the dimensions of the original signal \( f \), \( M \) for measuring dimension, and \( M < < N \)). Using this matrix to reconstruct the signal \( f \). Namely, the measurement matrix phi multiplied by signal \( f \) can be expressed as:

\[
 u = \Phi f = \Phi \Psi x = \tilde{\Psi} x
\]

Each line in phi can be treated as a sensor, multiplied by a reconfigurable signal \( f \). In the above formula, \( \tilde{\Psi} = \Phi \Psi \) is called the reconstruction matrix, and \( u \) can be regarded as the measured value of sparse signal \( x \) with respect to \( \tilde{\Psi} \).

In practical applications, engineers are more concerned about judging whether a certain reconstruction matrix can reconstruct a signal with a certain degree of sparsity and how much
reconstruction data is needed. The realization of the grid harmonic reconstruction matrix is a necessary condition for the intelligent reconstruction to be practical. The implementation of the harmonic reconstruction matrix of the power grid has pushed forward the practical application of the power grid harmonic signal. Due to the lack of effective discriminant theory of the reconstruction matrix, all other methods, except the single-pixel camera of rice university\cite{7}, lack of strict theoretical analysis.

To sum up, the purpose of power network harmonic signal reconstruction is to minimize the reconstructed data. Therefore, the following principles should be followed:

1) as little data as possible should be collected;
2) facilitate the implementation of optimization algorithm;
3) universality.

2.4 Network harmonic signal reconstruction algorithm

In the theory of power grid harmonic signal reconstruction, the difficulty of signal reconstruction algorithm\cite{8} is to identify the position of the largest element in the target signal. Power grid harmonic signal reconstruction algorithm is inspired by the tolerance constraint equidistant condition. When the reconstruction matrix $\Psi^*$ meets the constraint equidistant condition, vector $y = \mu = \Psi^* x$ is taken as the signal agent of sparse signal x with sparse degree K. Because of K element in the vector y energy approximation of K element of x is equal to the power grid harmonic signal energy, signal y K sparse component in the largest element of corresponding sparse signal x's largest element, because

$$\mu = \Psi x$$

is refactoring sampling value, to get just the refactoring $y = \Psi x$ samples values on the basis of times

$$\Psi^*$$

, so implementation process is very simple.

The grid harmonic signal reconstruction algorithm adopts iterative operation to approach the target signal\cite{9}. In each iteration, a redundant error is generated between the previous and the current approximation value, and the redundant error contains the target component in the target signal that has not been approximated. With the running of the algorithm, the redundant error value is updated to construct a new redundant signal proxy to further identify the largest element in the current component and prepare for the next iteration. This iterates until the energy of the original signal is restored.

The harmonic signal reconstruction algorithm requires four inputs, namely known conditions: the perceptive observation matrix $\Psi$; The compressed sampling vector $\mu = \Psi x$ of the unknown sparse signal x; Sparse degree K of sparse signal x; Stop iteration conditions.

The power grid harmonic signal reconstruction algorithm is described as follows:

1) Initialization: initial iteration times $t=1$; The approximate value $a$ of sparse signal x and all elements of initial value $a_{t-1}$ are set to zero, and the upper right corner of $a_{t-1}$ indicates the current iteration times. The initial redundancy error is the compressed sampling vector $v=\mu$.

2) Power grid harmonic signal calculation agent:

$$y = \Psi^* v$$

3) 2K maximum elements in the power grid harmonic signal proxy $y$ are selected:

$$2 su (kpp y)$$

4) Combined support volume: $T = \Omega \cup su pp(a_{k-1})$; Where, $a_{k-1}$ represents the vector composed of K maximum elements in the current approximation value of t-1 iteration number $a$.

5) Least squares signal estimation: $b_{\sim} = \Psi^* u, b_{\sim} = \{0\}$; Where $\Psi^*$ represents the inverse matrix of $\sim \Psi$, and the formula is $\sim \Psi^* = (\sim \Psi \Psi^*)^{-1} \sim \Psi^*$. 


(6) Pruning: \( a' = b_k, b_k \) means that only \( K \) maximum elements in the calculation result of \( b_k \) are taken.

(7) Update of redundant sampling values: \( v = u - \Psi a' \)

(8) If the iteration stop condition is not met, then the iteration number \( t=t+1 \), repeat steps (2)-(7) for the next iteration; Otherwise, the iteration is completed to obtain the approximate value \( a \) of the sparse vector \( x \).

It can be seen that the network harmonic signal reconstruction algorithm is a fast algorithm for network harmonic signal reconstruction. Under the condition of known sparsity \( K \), the harmonic signal reconstruction algorithm of the power grid directly selects \( K \) atoms from the dictionary, as shown in FIG. 2.

![Figure 2. Grid harmonic signal reconstruction algorithm flow chart](image-url)

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**Start**

- **Initialization**: Original harmonic sequence \( f \), Sparsity \( K \), Measurement matrix \( \Phi \), Sparse transformation basis \( \Psi \), Observation matrix \( \tilde{\Phi} \), Compressed Sampling
- **Observation vector** \( \tilde{y} = \tilde{\Phi} f \), The approximate value of coefficient \( c \), Matrix is set to \( 0 \), Iteration error value \( \epsilon \)

**Iteration times**: \( t=1 \)

- **Signal agent**: \( y = \Phi^* y \)

- **2K Maximum Elements in \( Y \)**: \( \Omega = \text{supp}(y_{2K}) \)

- **Consolidated support**: \( T = \Omega = \text{supp}(a') \)

- **Least Square Estimation**: \( \Psi_c = \Psi_{2K}, a_{2K} = [0] \)

- **Prune**: \( a' = b_k \)

- **Redundancy error**: \( v = u - \Psi a' \)

- **Satisfies the iteration stopping condition?**

- **Sparse Vector Reconstruction Value**: \( \tilde{x} = a \)

- **Reconstructing Harmonic Signal**: \( \tilde{f} = \Psi \tilde{x} \)

**End**
2.5 Realize the harmonic signal reconstruction of power network

Based on the sampling value of harmonic signal reconstruction obtained under multi-objective interference, the original harmonic signal can be reconstructed by using the harmonic signal reconstruction algorithm of the power grid, and the existing harmonic signal intelligent reconstruction method of the power grid can be used to detect the harmonic signal reconstruction, which corresponds to the traditional idea. In fact, for the problem of power grid harmonic detection, considering the intelligent reconstruction detection framework of power grid harmonic signals under multi-objective fault interference, if the basic and each harmonic signal can be detected directly from the reconstructed sampling data, the original harmonic signal need not be reconstructed. Inspired by the intelligent reconstruction algorithm of power grid harmonic signals, this paper proposes a method to detect the harmonic signal reconstruction directly from the reconstructed sampling values, which is named as the intelligent reconstruction method of power grid harmonic signals under multi-objective fault interference \[10\].

At present, for most existing harmonic signal reconstruction algorithms, the signal sparsity K must be known. However, in practical applications, the signal sparsity K cannot be obtained directly or can only be obtained by the estimation method, and the resulting estimation error will affect the accuracy of the harmonic signal reconstruction algorithm of the power grid. If the signal sparsity cannot be estimated in advance or the estimation deviation is large, it will become a bottleneck in practical application.

The same is true for harmonic signals in power grids, which are often unpredictable. Therefore, if the traditional idea is adopted, that is, harmonic signal is reconstructed one by one, sampling one by one, transmission one by one or storage one by one reconstruction algorithm one by one, signal reconstruction detection one by one will increase the complexity of calculation \[11\], on the one hand; on the other hand, if the sparse degree K is improperly selected, it will cause large errors. Another idea is to avoid the reconstruction algorithm and directly detect the harmonic signal, that is, harmonic signal reconstruction method to transmit or store the detection of harmonic signal one by one. The idea of harmonic signal detection here is still based on the traditional algorithm, but it is no longer aimed at the reconstruction of the whole harmonic signal, but the detection of harmonic signals one by one. Taking the Fourier transform basis as an example, the frequency characteristics of each harmonic component are two spectral lines. Specifically, one spectral line in the unilateral spectrum represents a harmonic signal, while the two symmetrical spectral lines in the bilateral spectrum represent a harmonic signal. In this paper, bilateral spectral mode is adopted, so the sparsity of each harmonic component K=2 can be determined. It can be seen that the sparsity in the network harmonic detection algorithm is a certain quantity, which avoids the error caused by sparsity estimation.

3. Experimental study

In order to detect the intelligent reconstruction method of power network harmonic signal based on multi-objective fault interference proposed in this paper, a simulation experiment is designed.

The experimental simulation signal is:

\[
f(t) = \sin(2\pi \times 50t) + 0.3\sin(2\pi \times 3 \times 50t) + 0.2\sin(2\pi \times 5 \times 50t)
\]

Where, the amplitude unit of harmonic signal is pu. In order to ensure the accuracy of the comparison experiment, the sampling frequency was determined to be 6400Hz, the amplitude of the harmonic signal a= 0.2A, and the frequency f=150Hz. The experimental reconstruction method adopts the intelligent reconstruction method of power grid harmonic signal under multi-objective fault interference and the original power grid harmonic signal intelligent reconstruction method to detect the simulation signal accuracy.

The following figure shows the detection results of reconstructed sampling harmonic signals by the detection method of power network harmonic signal reconstruction. Figure 3 shows the accuracy detection results of the original harmonic signal intelligent reconstruction method represented by the simulation signal. Figure 4 shows the precision detection results of the intelligent reconstruction method of power grid harmonic signals under multi-objective fault interference. Figure 5 shows the
detection error of the power grid harmonic signal detection algorithm. As can be seen from the figure, the method proposed in this paper is very effective in detecting harmonic signals of the power grid. Without reconstruction, the accuracy of harmonic signals of the power grid can be directly and accurately detected, and the detection error is less than 0.01%.

Figure 3. Precision detection results of original power grid harmonic signal intelligent reconstruction method

Figure 4. Precision detection results of the intelligent reconstruction method of harmonic signal in power network under multi-objective fault interference

Figure 5. Detection error of power network harmonic signal detection algorithm

The figure above shows the comparison between the intelligent reconstruction method of harmonic signal of power grid under multi-objective fault interference and that of original power grid. Under the multi-objective fault interference, the detection result of the harmonic signal in the intelligent reconstruction method of the power grid is exactly consistent with the expected value, and the maximum error of the detection result of the harmonic amplitude is 0.15%, which reflects the high-precision detection effect. In contrast, the harmonic frequency measured by the original power grid harmonic signal intelligent reconstruction method is quite different from the expected value, with a maximum error of 5% [12]. It can be seen that the intelligent harmonic signal reconstruction method proposed in this paper has higher detection accuracy than the original harmonic signal intelligent reconstruction method, and avoids the signal reconstruction process, so the algorithm is simple and efficient.

4. Conclusions

In this paper, an intelligent reconstruction method of power network harmonic signal under multi-objective fault interference is proposed. Firstly, the original harmonic signal is compressed and sampled based on multi-objective fault interference. Then, the harmonic signal reconstruction algorithm is applied to detect and separate the sampled sequence values without estimating the sparsity. Compared with the traditional signal reconstruction detection method, this method does not need to reconstruct the initial signal completely before signal detection. Power grid harmonic signals intelligence reconstruction method only needs few sampling points can be accurate reconstruction for the original harmonic signal detection, to reduce the burden of the analog/digital sampling equipment, save the storage space of the intermediate variable, can directly from the power grid harmonic signal to detect the interested in power grid harmonic signal, has the very high application value. It is hoped that the research in this paper can provide reliable basis for harmonic signal detection of power grid and promote the development of national economy.

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