Impulse Noise Suppression based Iterative Hybrid Nonlinear in Power Line Communication

Deyang Teng1*, Yanxi Zheng2, Kai Zhang1, Shilin Zhao1, Hairong Zhang1

1Skills training center of State Grid Sichuan Electric Power Company, Chengdu 610072, China
2Information and Communication Company of State Grid Sichuan Electric Power Company, Chengdu 610041, China
Email: 853529456@qq.com, 1406952290@qq.com
tengdeyang@scdy.edu.cn*

Abstract: In power line orthogonal frequency division multiplexing (OFDM) communication systems, the presence of impulse noise can seriously affect system performance. One of the conventional solutions is to perform a mixed nonlinear processing on the time domain signal at the receiving end before performing subsequent OFDM demodulation. Therefore, this thesis studies an improved method based on iterative elimination of nonlinear distortion. Firstly, the received OFDM signal is subjected to hybrid nonlinear processing in the time domain. Secondly, the nonlinear distortion introduced by the time domain nonlinear processing is reconstructed by the symbols initially detected in the frequency domain, and the reconstruction accuracy is improved by iteration. Finally, the reconstructed nonlinear distortion is subtracted from the output of the hybrid nonlinear processing unit. The simulation results show that compared with the traditional hybrid nonlinear method, the performance of the proposed algorithm is much better than that of the traditional algorithm.

1. Introduction
Power line communication technology is an important foundation to ensure the safe and stable operation of the power grid. In recent years, with the rapid development of smart grids, power communication technology, as an important support for smart grids, can be widely used in fields such as smart meter reading, dynamic billing, metering control, and smart monitoring; in addition, power line communication technology can also use the existing power network to transmit information. Power line communication technology has the advantages of wide line coverage and low operating costs, so it has received great attention[1]. However, the original intention of constructing a power grid is to transmit electrical energy, not to transmit data. There are many branches and devices on the power network, with varying line impedance, severe channel loss, and various noise interference. Power lines are not suitable for signal transmission. To solve this problem, Orthogonal Frequency Division Multiplexing is used as the main technology of power line communication. As an effective multi-carrier technology, OFDM can divide the channel into several sub-channels for data transmission. The signals of several sub-channels are orthogonal to each other and have the same frequency interval. This method can effectively improve spectrum utilization and reduce channel loss. It can reduce the influence of various noises on signal transmission.

Compared with other communication systems, there are a lot of noises in power communication...
systems and cannot be simply summarized as Gaussian white noise. The noise in the power communication system is usually divided into five types[2]: colored background noise, narrow-band noise, periodic impulse noise asynchronous with power frequency, periodic impulse noise synchronous with power frequency, and random impulse noise. The first three types of noise have relatively stable periods and slow changes in amplitude over time, collectively referred to as background noise. The latter two types of noise are summarized as impulse noise.

Impulse noise is generally caused by the switch of power equipment, and the noise amplitude changes very rapidly, which will seriously affect the communication quality. In order to combat the impulse noise in the PLC system, a large number of researchers have conducted research on impulse noise suppression technology. Commonly used methods are nonlinear method [3-6], compressed sensing method [7] and iterative method [8]. Among them, the nonlinear method is very popular due to its simple implementation and low complexity. According to the processing method, the nonlinear method can be divided into "zero-setting" nonlinear, "limiting" nonlinear and "hybrid" nonlinear methods. Compared with the first two nonlinear techniques, hybrid nonlinear performance is better [6]. However, the hybrid nonlinear method can produce sub-carrier interference while suppressing impulse noise, causing nonlinear distortion, and its performance is still far from the ideal performance upper limit.

2. System Model

2.1 OFDM System Model

This article uses the OFDM-based broadband PLC system model, the model is shown in Figure 1.

First, perform convolutional coding and interleaving on the information bits at the transmitting end, and then perform constellation mapping to obtain the transmitted symbol \( \{X_k\}_{k=0}^{N-1} \). The transmitted signal \( \{X_k\}_{k=0}^{N-1} \) then undergoes N-point inverse fast Fourier transform (IFFT) to obtain the OFDM transmission signal, As shown in formula (1)

\[
x_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k \cdot e^{\frac{j 2\pi k n}{N}}, \quad n = 0,1,\cdots,N-1
\]

In addition, in order to meet the requirements of baseband communication, \( \{X_k\}_{k=0}^{N-1} \) must have conjugate symmetry to obtain the real baseband transmission signal \( x_n \).

The transmission of signal \( x_n \) in PLC channel \( \{h_n\}_{n=0}^{L-1} \) will be severely disturbed by noise, including background noise and impulse noise. If ideally, the transmitted signal \( x_n \) can solve the inter-symbol interference problem by adding an infinite length cyclic prefix (Cyclic Prefix, CP), then the received signal \( r_n \) after de-CP can be obtained.
Where, \( s_n \) — the output signal of channel PLC

\( u_n \) — pulse noise

\( w_n \) — background noise

### 2.2 Channel Model

Due to the numerous branches and complex equipment in the power line communication network, the channel is seriously affected by multipath. In order to analyze the performance of noise suppression more accurately, this paper chooses the power line multipath channel model in literature [9]. This model is a classic model proposed by M. Zimmermann and K. Dostert, which can effectively show the characteristics of frequency attenuation and multipath.

### 2.3 Noise Model

Considering the amplitude and time characteristics of noise in the power line communication system, this paper uses the Bernoulli-Gaussian(BG) model to model the noise [10]. In the BG model, the background noise \( w_n \) is represented by additive white Gaussian noise with a mean value of 0 and a variance of \( \sigma_w^2 \), and the occurrence of random noise \( u_n \) is represented by the Bernoulli Gaussian process. The calculation formula of \( u_n \) is shown in (1).

\[
\begin{align*}
    u_n &= b_n g_n, & n &= 0, 1, 2, \ldots, N - 1 \\

\end{align*}
\]

### 3 Impulse Noise Elimination

#### 3.1 The Nonlinear Method

In order to suppress the impact of impulse noise, usually a memoryless nonlinear module can be added in front of the OFDM demodulator at the receiving end, as shown in Figure 2. According to different nonlinear processing methods, the commonly used nonlinear methods are as follows [3-6]:

##### 3.1.1. Zero-setting nonlinear method

\[
y_n = \begin{cases} 
    r_n, & |r_n| \leq T_i \\
    0, & |r_n| > T_i 
\end{cases}
\]
T₁ represents the zero-setting threshold.

3.1.2. Limiting nonlinearity

\[ y_n = \begin{cases} 
  r_n, & |r_n| \leq T_2 \\
  T_2 \text{ sgn}(r_n), & |r_n| > T_2 
\end{cases} \]  

(7)

T₂ represents the limiting threshold.

3.1.3. Hybrid nonlinear method

\[ y_n = \begin{cases} 
  r_n, & |r_n| \leq T_1 \\
  T_1 \text{ sgn}(r_n), & T_1 < |r_n| \leq T_2 \\
  0, & |r_n| > T_1 
\end{cases} \]  

(8)

Among them, \( T_1 = \alpha T_2 \) (\( \alpha > 1 \)).

Figure 2. Block diagram of the nonlinear method.

It can be seen from equations (6)-(8) that although the three non-linear methods eliminate the main impulse noise, they also produce varying degrees of distortion in the signal components in the samples containing impulse noise. Due to the better performance of hybrid nonlinearity [6], let's take hybrid nonlinear method as an example, focus on analyzing the nonlinear distortion introduced by it, and propose corresponding hybrid nonlinear distortion elimination methods.

3.2 Non-linear Distortion Analysis

From the above analysis, it can be seen that the signal distortion produced by the hybrid nonlinear processing exists on those samples that are zeroed or limited, and the hybrid nonlinear processing can record the positioning information on the samples one by one. In order to analyze the signal distortion introduced by hybrid nonlinear processing, we define

\[ b_n = \begin{cases} 
  0, & n \in \Theta \\
  1, & n \notin \Theta 
\end{cases} \]  

(9)

\[ c_n = \begin{cases} 
  1, & n \in \Phi \\
  0, & n \notin \Phi 
\end{cases} \]  

(10)

\( \Theta = \{n \mid T_2 < |r_n| \leq T_1, n \in Z^+ \} \) represents the position index set of the samples whose amplitude is greater than the threshold \( T_2 \) and less than or equal to the threshold \( T_1 \); \( \Phi = \{n \mid |r_n| > T_2, n \in Z^+ \} \) represents the position index set of the samples whose amplitude is greater than the threshold \( T_2 \).

Convert the output of the hybrid nonlinear unit in the above equation (8) into the following way

\[ y_n = b_n \cdot [s_n + z_n] + T_1 \cdot c_n 
= b_n s_n + T_1 c_n + z'_n \]  

(11)

\( z'_n = b_n \cdot z_n \) is the total noise term after mixed nonlinear processing.

After the receiver adopts Fast Fourier Transform (FFT) to the output of the hybrid nonlinear unit, it is convenient to demodulate the OFDM signal. Output can be obtained by FFT.
\[ Y_k = \frac{1}{N} B_k \otimes S_k + T_z \cdot C_k + Z'_k \]  

The symbol "\( \otimes \)" represents cyclic convolution; \( B_k, S_k, C_k \) and \( Z'_k \) represents the fast Fourier transform of, \( b_k, s_k, c_k \) and \( z'_k \).

The above formula (12) can be expressed in the form of matrix multiplication.

\[ Y = \frac{1}{N} \begin{bmatrix} B(0) & B(N-1) & \cdots & B(1) \\ B(1) & B(0) & \cdots & B(2) \\ \vdots & \vdots & \ddots & \vdots \\ B(N-1) & B(N-2) & \cdots & B(0) \end{bmatrix} S + T_c \cdot C + Z' \]

\[ = \frac{1}{N} PS + T_c \cdot C + Z' \]  

In the above formula, \( Y, S, C \) and \( Z' \) represents the matrix form of \( Y_k, S_k, C_k \) and \( Z'_k \); \( P \) represents the \( N \) points cyclic convolution matrix of \( B_k \).

In order to further simplify formula (13),In this paper, \( P \) is represented as \( P = P_1 + P_2 \), \( P_1 \) represents the \( N \)-dimensional diagonal matrix formed by the diagonal elements of \( P \) in formula (14), and \( P_2 \) represents the \( N \times N \) matrix formed by other elements of \( P \). Then formula (13) can be simplified to get

\[ Y = \frac{1}{N} (P_1 + P_2) S + \alpha T_c \cdot C + Z' \]

\[ = \frac{N_c}{N} S + \frac{1}{N} P_2 S + \alpha T_c \cdot C + Z' \]

\[ = \alpha S + \left( \frac{1}{N} P_2 S + \alpha T_c \cdot C \right) + Z' \]  

\( N_c \) represents the number of samples in an OFDM signal whose amplitude is less than or equal to the limiting threshold \( T_2 \), assuming \( \alpha = N_c / N \).

It can be seen from the above formula that the nonlinear distortion generated during the application of the hybrid unrestricted method mainly includes two types: the first type is to attenuate the information signal to \( \alpha \) times of itself, that is, the first term of the formula; the second type is to generate The sub-carrier interference is the second term of the formula. In addition, according to equation (15), the frequency domain expression of nonlinear distortion can be obtained as

\[ D = (\alpha - 1) S + \left( \frac{1}{N} P_2 S + \alpha T_c \cdot C \right) \]

The corresponding time domain expression is

\[ d_n = (\alpha - 1) s_n + (b_n - \alpha) s_n + T_c \cdot c_n \]

\[ = (b_n - 1) s_n + T_c \cdot c_n \]  

### 3.3 Iterative Nonlinear Distortion Elimination

In the above analysis, we have obtained the nonlinear distortion time-domain expression shown in equation (17). Among them, \( b_n \) and \( c_n \) can be obtained by the hybrid nonlinear unit, and \( s_n \) is unknown, but the initial decision symbol can be used to obtain its estimate \( \tilde{s}_n \). Therefore, in order to further improve the performance of the hybrid nonlinear method, we propose an improved algorithm as shown in Figure 3. The specific steps of this method are as follows:
1) First, perform hybrid nonlinear processing on the time-domain received signal $r_n$ to obtain $y_n$, and then perform FFT on $y_n$ to obtain $Y_k$.

2) Then, signal $\hat{X}_k^{(l)}$ is obtained by using channel equalization and symbol decision on $Y_k$, and then $\hat{X}_k^{(l)}$ is passed through the inverse process of channel equalization, that is the estimated value $\hat{S}_k^{(l)}$ of $S_k$ which is divided by the equalization coefficient $G_k$.

3) After that, the estimated value $\hat{S}_k^{(l)}$ is converted to the time domain by FFT to obtain $\hat{x}_k^{(l)}$, and then the signal distortion $\hat{d}_a^{(l)}$ produced by mixed nonlinear processing is reconstructed according to equation (17).

4) Finally, the reconstructed nonlinear distortion $\hat{d}_a^{(l)}$ is subtracted from $y_n$, as shown in equation (18).

$$y_n^{(l)} = y_n - \hat{d}_a^{(l)}$$

We can increase the accuracy of reconstruction of mixed nonlinear distortion by repeating the above algorithm steps. Where $l$ represents the number of iterations, and $y_n^{(0)} = y_n$ in the process of cyclic iteration, each iteration can eliminate partial distortion. After a certain number of iterations, the hybrid nonlinear distortion elimination can achieve a better state.

As can be seen from the above figure, each iteration of the hybrid nonlinear algorithm based on iteration needs a series of operations, such as FFT, channel equalization, symbol decision, IFFT and hybrid nonlinear distortion reconstruction. Therefore, compared with the hybrid nonlinear method, the computational complexity of the proposed algorithm is reduced to a certain extent by increasing the computation amount of these processes.

### 4. Result

In this paper, the multi-path channel model proposed by M. Zimmermann is used to model the channel. The power line 4-path channel model is adopted. The simulation parameters are shown in Table 1. In the simulation, the number of FFT points is 1024, the 1/2 convolutional coding method is adopted, and the constellation mapping mode is QPSK.

| Table 1. Simulation parameters. |
|----------------------------------|
| **Attenuation parameter** | $k_0 = 1$, $a_0 = 0$, $a_i = 7.8 \times 10^{-8} \text{ m/s}$ |
| **Path parameter** |   |
| $i$ | $g_i$ | $d_i / \text{m}$ | $i$ | $g_i$ | $d_i / \text{m}$ |
| 1 | 0.64 | 200 | 3 | -0.15 | 244.8 |
| 2 | 0.38 | 222.4 | 4 | 0.05 | 267.5 |
Figure 4. Bit error rate performance of hybrid nonlinear and proposed algorithm under different thresholds.

Figure 4 shows the effect of threshold $T$ ($T_i$) on the performance of iterative based hybrid nonlinear algorithm with SNR of 20dB, SINR of -15dB and pulse noise rate of 0.02. In the simulation, the threshold $T$ varies from 0 to 6. The research in reference[4] shows that the optimal scaling factor $\alpha$ is usually 1.8 at low SINR (-6db-15db). Therefore, in the simulation, $\alpha$ is set to 1.8. It can be seen from the figure that the performance of the improved algorithm is obviously better than that of the hybrid nonlinear method. With the increase of the number of iterations, the performance of the improved algorithm is continuously improved, and it has converged in the third iteration. Compared with the mixed nonlinear method, the bit error rate is reduced from $8 \times 10^{-3}$ to $1.5 \times 10^{-3}$. In addition, it can be seen that the improved algorithm also has an optimal threshold, and the optimal threshold tends to decrease with the increase of iteration times. The reason is that the more iterations, the stronger the ability to deal with nonlinear distortion. It can suppress impulse noise by reducing the optimal threshold.

Figure 5. Bit error rate performance of improved algorithm under different impulse noise rates.
Figure 5 shows the effect of impulse noise rate $P$ on the performance of iterative based hybrid nonlinear algorithm when SNR is 20dB and SINR is -15dB. It can be seen from the simulation diagram that when the pulse noise rate $P$ gradually increases, the bit error performance of the algorithm will be reduced; in addition, by comparing different pulse noise rate $P$, we can see that when the pulse noise rate gradually increases, the optimal threshold value will be reduced accordingly. The reason is that when the impulse noise rate $P$ increases gradually, the number of samples disturbed by impulse noise will also increase. It can also suppress impulse noise by lower optimal threshold.

Figure 6. Bit error rate performance of hybrid nonlinear and improved algorithms under different SNR.

Figure 6 shows the BER performance of the hybrid nonlinear method and the improved algorithm under different SNR when SINR is -15dB and $P$ is 0.02. Among them, the threshold used in the simulation is the optimal threshold obtained through a large number of threshold simulation. It can be seen from the simulation diagram that the performance of the improved algorithm is improved obviously in one iteration, and the BER performance of the algorithm has already converged when the iteration is 2 or 3 times. Moreover, it can be seen from the simulation diagram that in the high SNR state, the bit error rate of the improved algorithm after three iterations is lower than that of the first iteration; in the low SNR state, the bit error rate of the improved algorithm after three iterations and one iteration is almost the same, because there are many wrong decisions in the low SNR state, which will produce a lot of BER transmission. However, it can be seen from the simulation diagram that although the performance of the improved algorithm is improved after several iterations, there is still a certain gap compared with the Gaussian white noise, because some impulse noise amplitude is lower than the threshold value and can not be detected and eliminated.

5. Conclusion
Aiming at the problem of nonlinear distortion caused by hybrid nonlinear method in suppressing impulse noise, an improved hybrid nonlinear impulse noise suppression method based on iteration is studied in this paper. The algorithm uses the power line multipath channel model to process the OFDM signal in the time domain; secondly, the nonlinear distortion is reconstructed according to the signal detected in the frequency domain, and the accuracy of the reconstruction process is improved by
iteration. The simulation results show that the improved algorithm has good convergence speed, and can improve the performance significantly with less iterations. When SNR is 20dB, SINR is - 15dB, P is 0.02, the improved algorithm can reduce the bit error rate from $8 \times 10^{-3}$ to $1.5 \times 10^{-4}$ compared with the hybrid nonlinear method.

Reference:
[1] Sharma, K., Saini, L.M. (2017) Power-line communications for smart grid: Progress, challenges, opportunities and status. Renewable and Sustainable Energy Reviews, 67:704-751.
[2] Yiwen, C., Bin, X., Jianhua, H. (2015) Modeling and simulation of power line communication system based on OFDM technology. Foreign Electronic Measurement Technology, 34(02):21-26.
[3] Juwono F. H., Guo Q., Huang D., et al. (2016) On the Performance of Blanking Nonlinearity in Real-Valued OFDM-based PLC. IEEE Transactions on Smart Grid, 28(9):1-8.
[4] Rabie K. M., Alsusa E. (2014) Quantized peak-based impulsive noise blanking in power-line communications. IEEE Transactions on Power Delivery, 29(4): 1630-1638.
[5] Juwono F. H., Guo Q., Huang D., et al. (2014) Deep clipping for impulsive noise mitigation in OFDM-based power-line communications. IEEE Transactions on Power Delivery, 29(3): 1335-1343.
[6] Zhidkov S. V. (2008) Analysis and comparison of several simple impulsive noise mitigation schemes for OFDM receivers. IEEE Transactions on Communications, 56(1): 5-9.
[7] Lin J., Nassar M., Evans B. L. (2013) Impulsive noise mitigation in powerline communications using sparse Bayesian learning. IEEE Journal on Selected Areas in Communications, 31(7): 1172-1183.
[8] Mengi A., Vinck A. J. H. (2010) Successive impulsive noise suppression in OFDM. In: 2010 IEEE International Symposium on Power Line Communications and Its Applications. Rio de Janeiro, Brazil.pp. 33-37.
[9] Jili W., Daoxing G.. (2016) Blind Synchronization Algorithm For LS-based OFDM in Powerline Channel. Communications Technology, 49(09):1129-1133.
[10] Herath S. P., Tran N. H., Lengoc T. (2015) Optimal Signaling Scheme and Capacity Limit of PLC Under Bernoulli-Gaussian Impulsive Noise. IEEE Transactions on Power Delivery, 30(1):97-105.