*Article*

# Impulsive Noise Characterization in Narrowband Power Line Communication

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**Abstract:** Currently, narrowband Power line communication (PLC) is considered as an attractive communication system in smart grid environments for applications such as advanced metering infrastructure (AMI). In this paper, we will present a comprehensive comparison and analysis in time and frequency domain of noise measured in China and Italy. In addition, impulsive noise in these two countries are mainly analyzed and modeled using two probability based models, Middleton Class A (MCA) model and $\alpha$ stable distribution model. The results prove that noise measured in China is rich in impulsive noise, and can be modeled well by $\alpha$ stable distribution model, while noise measured in Italy has less impulsive noise, and can be better modeled by MCA model.

**Keywords:** narrowband PLC; impulsive noise; noise modeling

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## 1. Introduction

Power Line Communications (PLC), is currently considered as an attractive communication system in smart grid because of its ubiquitous infrastructure and low-cost operation maintenance. Advanced metering infrastructure (AMI), based on narrowband PLC, can be applied in automatic meter reading (AMR), demand side response, real-time monitoring and vehicle charging in smart grid. It is well known that the PLC channel is a hostile medium for communication due to its multi-path effect , frequency selectivity, time varying properties and high noise levels.

For widespread narrowband PLC, four unified international standards are developed including PRIME, G3, IEEE P1901.2 and G.HNEM. According to the CENELEC (European Committee for Electrotechnical Standardization) frequency bands, all these four standards are applied in CENELEC A band (35.9-90.6KHz), while the utilization of the U.S. Federal Communication Commission (FCC) band is shown in Table 1.

An overview of the noise characteristics in narrowband PLC can be found in [1-2]. The available noise measurements have been carried out in distributed networks of different topologies in some countries, but they are conducted only in partial sub-bands of 3-500kHz, instead of covering the whole frequency band. In addition, noise measurements of many in-home devices (dimmers, universal motors, PC, etc) have also been conducted fin order to model the noise characteristics. For instance, see data for China [3], Brazil [4], USA [5],[7-9], Germany [6,10], France [5], Tunisia [11-12], Sweden [13], Japan [14] and Italy [15]. However, when collecting these available noise data, the measurement set-up is not always presented in a comprehensive manner.

Power line noise was firstly measured in frequency band of 0-100kHz, and classified into different types based on its characteristics in time and frequency domain [5]. According to [5], power line noise in broadband PLC lower than 20MHz was first categorized into five classes: colored background noise (CBG), narrowband interferences (NBI), periodic impulsive noise synchronous to mains frequency (PINS), periodic impulsive noise asynchronous to the mains frequency (PINAS) and asynchronous impulsive noise (AIN) in [16]. An empirical noise model was built based based on time and frequency domain observation, especially defining the basic characteristics of impulsive noise

such as impulse width, impulsive amplitude, interarrival time, impulse rate and the disturbance ratio. This noise classification was comprehensively applied in subsequent power line noise modeling in both broadband and narrowband PLC. Generally, the three types of impulsive noise (PIN, PINAS and AIN) are modeled as a single group (impulsive noise, IN) in broadband PLC, because of their fast time varying behaviour. This is due to the fact that, in broadband PLC, the time duration of one OFDM symbol or frame is far shorter than one mains period, thus cyclostationary property is seldom considered. In [17], impulsive noise was modeled in frequency domain considering the channel transfer characteristics between noise source and receiver. In [18], based on physical and statistical properties of impulsive noise such as in [16], impulsive noise was modeled by starting with specific noise measurement. Power line noise in narrowband PLC was also modeled considering the noise taxonomy proposed above [19]. However, in narrowband PLC, the time duration of one OFDM frame lasts longer than one mains period; therefore, the cyclostationary behavior has been examined in more detail [20]-[22]. The modeling methods above are based on noise physical characteristics in specific scenarios.

On the other hand, another way to describe the power line noise characteristics is based on the use of probability distribution, in which MCA model and $\alpha$ stable distribution are applied. Among all five classes of noise, NBI in broadband PLC is generally caused by radio waves, and is not considered in these methods. Besides, the three kinds of impulsive noise are considered together, instead of being modeled separately. Therefore, power line noise modeling based on probability distribution mainly attempts to characterize impulsive noise. The MCA model was proposed to describe natural or man-made electromagnetic disturbance, in which noise is mainly spectrally narrower compared to the receiver bandwidth [23]. Its probability density function (PDF) can be determined by only three factors: impulse index, the variance of background Gaussian noise to that of the impulsive power ratio, and background Gaussian noise variance, which makes it widely used in power line impulsive noise modeling. However, it fails to characterize noise temporary property, Markov-Middleton Model (MM) was proposed to characterize impulsive noise bursts, but they still share the same PDF [24]. Furthermore, it is proved that power spectrum density (PSD) of MCA model and Markov Middleton Model are similar and close to PSD of white noise [25]. The $\alpha$-stable distribution model was commonly employed to model impulsive noise in various physical environments including underwater acoustic noise, man-made audio noise, as well as different types of electromagnetic phenomena [26]. It was used to characterize power line impulsive noise in industrial zone [27] and in other scenarios based on measurement in frequency band of 0-50kHz in CEN A [28]-[29] . The $\alpha$-stable distribution has not yet been examined for the whole frequency band in narrowband PLC.

In this paper, power line noise indoors were measured both in China and Italy with different loads connected to the network, and the frequency range nearly embraces the whole frequency band from 30-500 kHz. We propose a statistical study of the main characteristics of the measured noise in both countries: we compare the basic noise characteristics both in time and frequency domain of two countries and apply two noise modeling techniques (MCA and $\alpha$-stable distribution) as well as inspecting their sustainability.

**Table 1.** Frequency bands applied in four Narrowband PLC standards in Europe and U.S.A.

| Frequency Range | PRIME | G3 | IEEE P1901.2 | G.HNEM |
|---|---|---|---|---|
| CEN A | 42-89kHz | 39.9-90.6kHz | 39.9-90.6kHz | 39.9-90.6kHz |
| FCC | / | 159.4-478.1kHz | 35.9-487.5kHz | 34.4-478.1kH |

## 2. Measurement Setup in China and Itlay

The measurement setup is shown in Fig.1. The main measurement instrument is a PXI digitizer (National Instrument). A PXI 5105 was used in China, whereas a PXI 5124 was used in Italy. Both digitizers have 12-bit resolution, and the maximum sampling speed is above 50MS/s. The digitizer was

connected to the low voltage network of 220V through a coupling filter and a digital signal processing software, LabVIEW, was used to record and process the collected data. The coupling filter circuit used in China is shown in Fig.2, and its measured transfer function is shown in Fig.3. The coupling filter used in Italy is similar, and it is described in [30]. In both cases the coupling filter acts as a band pass filter, with a -3dB attenuation in the band between 4 kHz (7 kHz in Italy) and 600 kHz, resulting in a large attenuation of the 50 Hz mains frequency. As explained before we focused on narrowband PLC noise measurement in the frequency range from 10 kHz to 600 kHz, a sampling frequency of 2MS/s is adopted in the measurement in both countries.

In order to evaluate the power line noise injected in the low voltage network by commonly used devices, a great number of measurements has been done when different loads are connected to the same multi-socket where the measurement setup is connected. The scope of this arrangement is to measure the noise that a narrowband PLC device would receive from the network when it is connected near to a commonly used device, in home or office environments. The connection of the load to the same socket is in general a worst case scenario, since the noise produced by the load is not attenuated by distance.

In China the measurements were carried out in both lab and home environments. In the lab environment, the noise was produced by a cellphone charger, a hairdryer, a screen and a PC, while in home environment, the noise was produced by a fridge, a TV and a washing machine. In Italy measurements were carried out in home environment, and the measured devices were a vacuum cleaner, a 1A cellphone charger, a washing machine, a hairdryer, a microwave oven, a 19A laptop charger, a 32 inches led TV, a fridge, a coffee machine and a charger for electric tooth cleaner that use wireless power transfer (WPT) technology. With a great number of measurement in different occasions, the noise comparison are conducted in a comprehensive and general way.
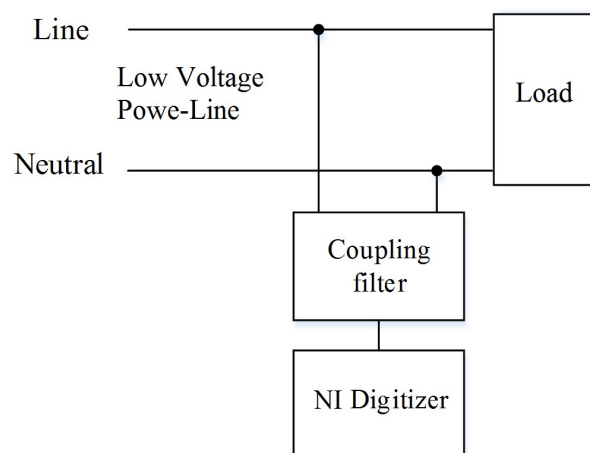


**Figure 1.** Measurement setup for noise collection.
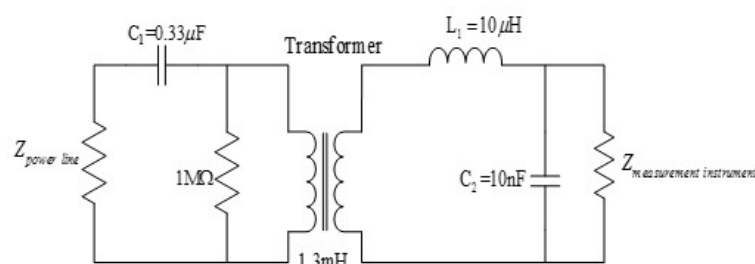


**Figure 2.** Coupling filter circuit.
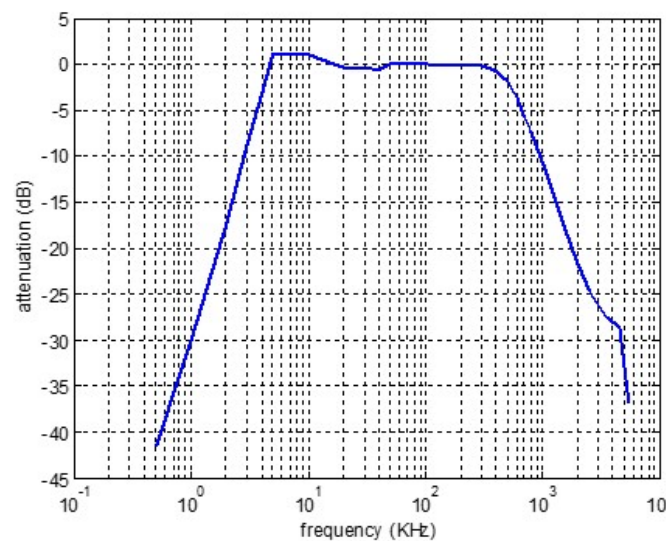
**Figure 3.** Transfer function of the coupling filter.

## 3. Basic time and frequency domain analysis of Noise

The noise data are collected in both countries in the frequency range of 10-600kHz; in light of the used frequency band in the current standards ranging from 35.9 to 487.5 KHz (as shown in table I), we will mainly focus on the frequency band from 30 to 500 kHz. Since the sampling frequency of our measurement is 2MHz, the collected noise will be down-sampled to the sampling frequency of 1MHz, and then will be filtered by a highpass filter with stop frequency of 20kHz (with -60dB attenuation), thus obtaining the data that will be used for the analysis. The analysis is performed in the frequency domain using PSD analysis over a long time window, and in the time domain by means of the short time Fourier transform (STFT).

### 3.1. Power Spectrum Density Analysis

The PSD was calculated using the Welch method [31], using a Hanning window, averaging the frequency content over a long observation time of one mains period (20ms). As shown in Fig.4, it can be observed that the average noise level in China is roughly 10-15 dBuV higher than the one in Italy, while they are at the similar level of around 42dBuV in the range of 220-320kHz. To some extent, noise measured in Italy can be regarded as white noise when frequency band is higher than 50kHz, ignoring the effects of NBI.

In narrowband PLC, NBI is usually caused by the loads connected in the network and its bandwidth is of less than 5kHz. This case is completely different from what happens in broadband PLC, where NBI is often caused by radio waves with bandwidth of around 75kHz. The PSD analysis shows that NBIs occur with the central frequency of 64.45kHz and 99.61kHz in noise measured in China, while they occur around 68.36kHz, 207kHz, 345.7kHz, and 482kHz, the odd multiples of 68.36kHz. In these cases, the bandwidth of NBI is lower than 8kHz.
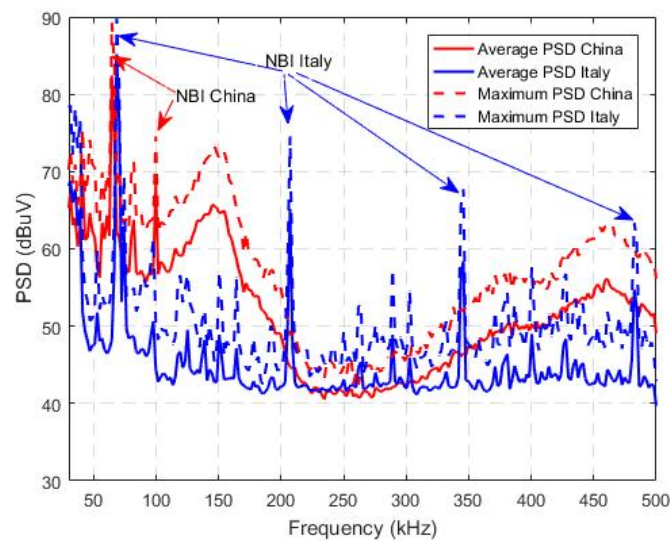
**Figure 4.** Noise PSD comparison between China and Italy.

*3.2. Time-Frequency Analysis*

Narrowband PLC noise in general shows cyclostationary behavior [3]. We calculated the spectrogram of the noise by means of the STFT, by using a Hanning window of length 128*us* (256 points FFT), and 50 % overlap. In both Fig.5 and Fig.6, the cyclostationary behavior of the noise, synchronous with the 100Hz, can be clearly observed.

NBI measured in China always exists in the frequency of 64.45kHz and 99.61kHz in Fig.5(b). PSD near 150kHz and 450kHz with wider frequency band remains high all the time, which can be seen as impulsive noise. Correspondingly, in Fig.5(a) impulsive noise occurs frequently in the whole time window, and even in the time window of 2-4 ms, the noise amplitude is lower but impulsive noise is still present, as it can be observed from the PSD near 450kHz with frequency range of around 100kHz in Fig.5(b).

NBI measured in Italy in Fig.6 lower than 100kHz occurs all the time, while its odd harmonics only occur in short time duration. It can be clearly seen that noise measured in Italy can be regarded as completely white noise without consideration of NBI. In Fig.6(a), the magnitude of noise increases suddenly near 4ms, and correspondingly, it displays higher power spectrum near 30kHz with bandwidth around 15kHz that is marked in red circles in Fig. 6(b), which also can be clearly seen in Fig.4.

It turns out that noise measured in China is full of impulsive noise all the time, while noise measured in Italy has hardly any impulsive noise but several NBIs. It's worth mentioning that NBI bandwidth is lower than 10kHz, while sometimes impulsive noise only occupies around 20kHz bandwidth in narrowband PLC. For this reason, when the noise bandwidth is near to 20kHz, it is hard to differentiate between NBI and impulsive noise only in the frequency domain.
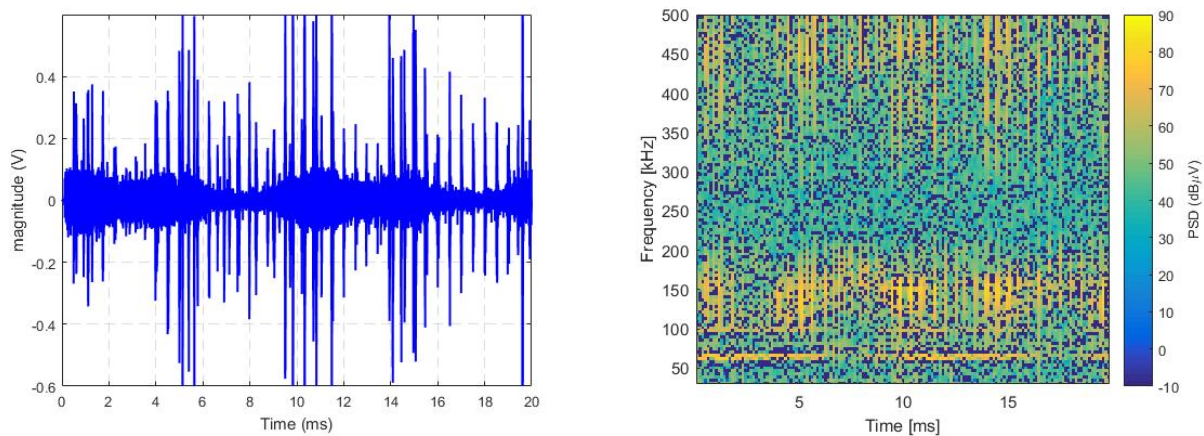
**Figure 5.** Noise measured in China (**a**) noise wave. (**b**) noise spectrogram .
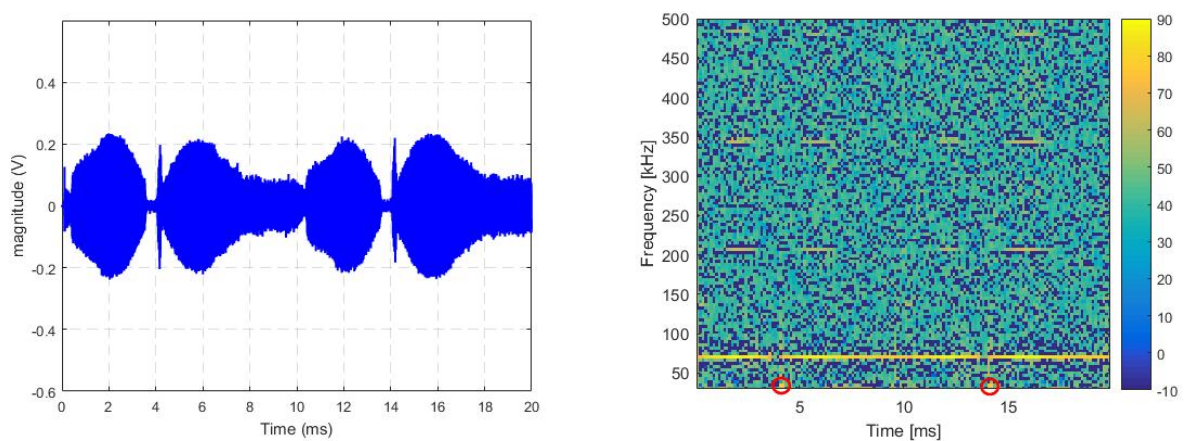


**Figure 6.** Noise measured in Italy (**a**) noise wave. (**b**) noise spectrogram .

## 4. Impulsive Noise Modeling

As a result from the previous basic noise characteristic analysis, both in time and frequency domain, we can say that impulsive noise is not negligible in both countries, especially in China. In this section, two kinds of impulsive noise models are applied to reproduce the measured results. Before modeling, the noise data are preprocessed by eliminating NBIs in the frequency domain, because the bandwidth is too narrow to design a low order finite impulsive response filter. The noise wave in Fig.5(a) and Fig.6(a) are filtered, as shown as in Fig.7 and Fig.8. After removing the NBI, it is even more evident the difference between the impulsive noise in the two countries: the amplitude of impulsive noise in China goes up to 1.2V; on the contrary it is lower than 0.2V in Italy.

Fig.7 displays that noise measured in China is characterized by frequent impulses of short time duration, while Fig.8 shows that impulsive noise with longer time duration occurs only twice per mains period in Italy, which means that the frequency band occupation of IN will be narrow, around 15kHz, located at the center frequency lower than 50kHz. In fact, all the noise measured in Italy with different loads connected in the network are as shown in Fig.8. All the measured noise in China has similar noise wave shown in Fig.7, but the impulsive noise occurrences vary from load to load.
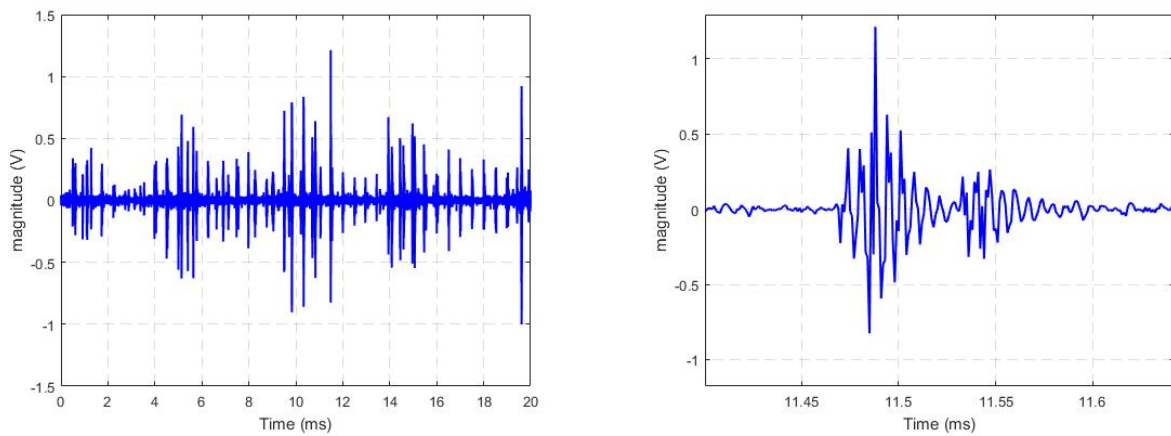
**Figure 7.** Noise measured in China without NBI (**a**) 20ms time windwow. (**b**) short time window.
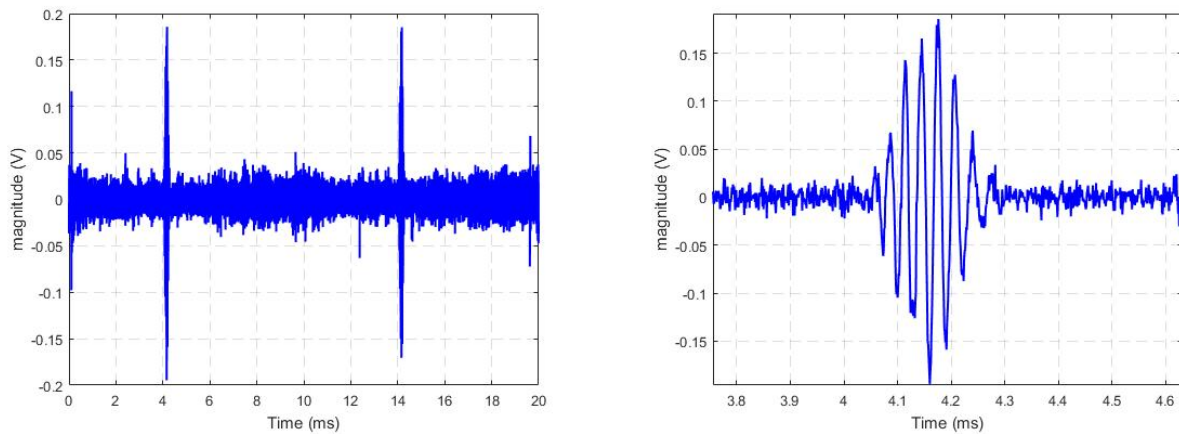


**Figure 8.** Noise measured in Italy without NBI (**a**) 20ms time windwow. (**b**) short time window.

*4.1. Model Methods*

4.1.1. Middleton class-A model

The middleton class A model is composed of two terms as

$$N(t) = N_G(t) + N_I(t) = N_G(t) + \sum_i U_j(t, \sigma), \tag{1}$$

where $N_G(t)$ is a stationary Gaussian noise and $U_j$ represents the j-th impulsive noise wave. The PDF of $N(t)$ can be expressed as a mixture of zero-mean Gaussian terms weighted by a Poisson process,

$$f_N(n) = \sum_{m=0}^{\infty} p_m \frac{1}{\sqrt{2\pi\delta_m^2}} e^{\frac{-n^2}{2\delta_m^2}}, \quad with \quad p_m = \frac{e^{-A}A^m}{m!}, \tag{2}$$

where the variances $\delta_m^2$ can be expressed as

$$\delta_m^2 = \delta_I^2 \frac{m}{A} + \delta_G^2 = \delta_G^2 \left( \frac{m}{A\Gamma} + 1 \right) \tag{3}$$

in which $\delta_G^2$ is the variance of $N_G(t)$, $\delta_I^2$ denotes the variance of impulsive noise $N_I(t)$, $\Gamma = \delta_G^2/\delta_I^2$, and $A$ is the impulse index, representing the density of impulses in one observed period. When building an MCA model, (2) will be truncated into $M$ finite mixtures of Gaussian noise, yielding

$$\tilde{f}_N(n) = \sum_{m=0}^{M-1} p'_m \frac{1}{\sqrt{2\pi\delta_m^2}} e^{\frac{-n^2}{2\delta_m^2}}, \quad with \quad p'_m = \frac{p_m}{\sum_{m=0}^{M-1} p_m}. \tag{4}$$

### 4.1.2. $\alpha$-stable model

The $\alpha$-stable distribution shows a slow tail decay; for this reason, the $\alpha$-stable distribution tends to generate large-amplitude excursions which can be used to describe impulsive noise. It doesn't have a closed expression of PDF but offers a characteristic function, consequently the PDF can be derived by the inverse fast Fourier transform (IFFT) of the characteristic function. The characteristic function $\Phi_X(\theta)$ of an $\alpha$-stable variable $X$ can be expressed as

$$\Phi_X(\theta) = \begin{cases} exp\{j\mu\theta - \sigma^\alpha|\theta|^\alpha(1 + j\beta sign(\theta)\tan(\frac{\pi\alpha}{2}))\} & \alpha \neq 1 \\ exp\{j\mu\theta - \sigma|\theta|(1 - j\beta\frac{2}{\pi}sign(\theta)\ln|\theta|)\} & \alpha = 1 \end{cases} \tag{5}$$

where $\theta \in \Re$ and

$$sign(\theta) = \begin{cases} 1 & if \quad \theta > 0 \\ 0 & if \quad \theta = 0 \\ -1 & if \quad \theta < 0 \end{cases} \tag{6}$$

In the above equations, there are four parameters: $\alpha$ is an index of stability when $0 < \alpha < 2$, the scale parameter $\delta$ ($\delta > 0$), the skewness parameter $\beta$ ($-1 < \beta < 1$) and shift parameter $\mu$ ($\mu \in \Re$). If $\beta = 0$, the variable $X$ will follow a symmetrical $\alpha$ stable distribution about $\mu$, referred as $S\alpha S$. As a matter of fact, $\beta$ can be used as a measure of the asymmetry.

### 4.2. Results of Impulsive Noise Modeling

The process of modeling the impulsive noise mainly concentrates on obtaining the parameters of each model to characterize the measured noise. In both models, maximum likelihood estimation (MLE) is applied for the parameters estimation.

### 4.2.1. Middleton Class A model

In the MCA model, three parameters must be estimated. The variance $\delta_G^2$ is derived from the background noise without impulsive noise, and the other two parameters $A$ and $\Gamma$ are estimated using MLE. The impulsive noise term $M$ is selected when the maximum likelihood reaches a steady value considering different noises measured with different loads. Fig.9 and Fig.10 show seven different noises (measured when different loads are connected) in China and Italy, respectively. It is evident that when $M$ is larger than 3, most of the parameters remains unchanged. Therefore, M is considered equal to 3, something that is also proposed in [32].

From Fig.9, it can be noted that impulse index $A$ in the noise measured in China is over 0.16, while it is lower than 0.04 in Fig.10. In addition, parameter $\Gamma$ is less than 0.7 in China, conversely, and it is higher than 0.75 in Italy, implying that the average background noise power is smaller in the whole noise power in China while, on the contrary, power line channel in China is greatly interfered by impulsive noise.
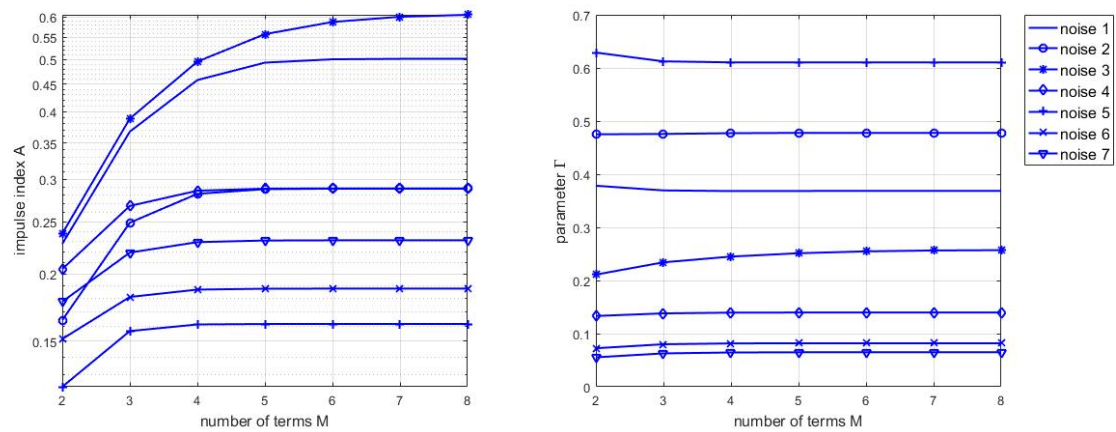
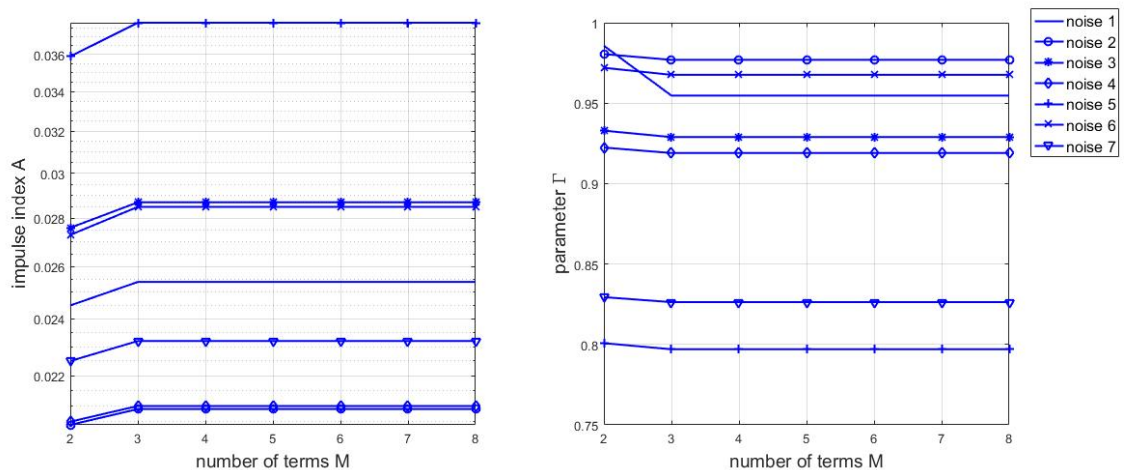**Figure 9.** A and Γ versus the number of terms *M* for noise measured in China



**Figure 10.** A and Γ versus the number of terms *M* for noise measured in Italy.

### 4.2.2. $\alpha$ stable distribution model

All four parameters in $\alpha$ stable distribution model are estimated by using MLE. In Tab.2, all the noise in China that have been previously modeled by MCA are examined also in this case. In the $\alpha$ stable distribution, when $\alpha = 2$, the distribution will reduce to the Gaussian distribution; when $\alpha < 2$, the distribution shows heavy tails that can be used to model the impulsive noise. Table 2 shows that $\beta$ is close to zero, meaning that noise waves are almost zero symmetrical, as the mean value $\mu$ is rather close to zero as well. For noise measured in Italy, as shown in Table 3, a similar conclusion can be reached that the noise is symmetrical with zero mean. Therefore, the model can be viewed as $S\alpha S$ distribution. Comparing $\alpha$ in Table 2 and Table 3, $\alpha$ of the noise in China is lower than the one in Italy; this corresponds to the previous frequency/time domain analysis in which we understood that power line channels in China are highly interfered by impulsive noise and $\alpha$ of noise in China varies greatly from load to load, while that of noise in Italy varies slightly.

**Table 2.** The parameters estimation of $\alpha$ stable distribution of noise in China.
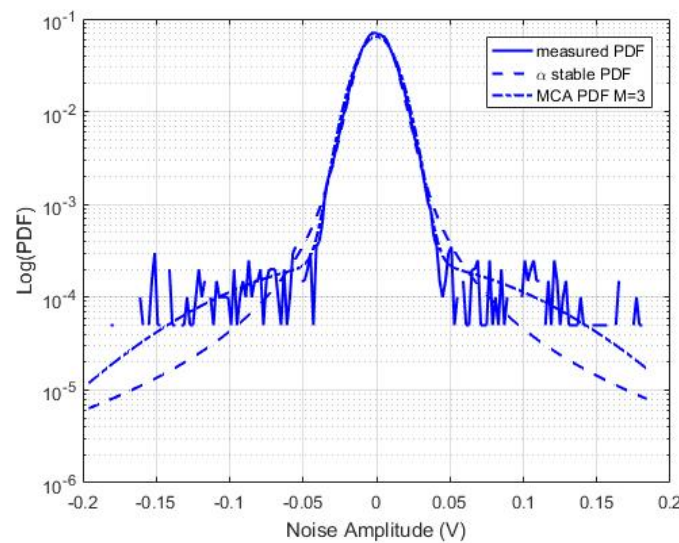
| noise | $\alpha$ | $\beta$ | $\delta$ | $\mu$ |
|-------|----------|---------|----------|-------|
| noise 1 | 1.59264 | -0.00636769 | 0.0189837 | 7.06E-06 |
| noise 2 | 1.56769 | -0.0165415 | 0.016261 | 9.62E-05 |
| noise 3 | 1.63601 | -0.0257861 | 0.0212625 | 2.10E-04 |
| noise 4 | 1.25285 | -0.00828737 | 0.0165645 | 3.28E-05 |
| noise 5 | 1.43699 | -0.00552512 | 0.012531 | 9.54E-06 |
| noise 6 | 1.21431 | -0.0104543 | 0.0148703 | 7.41E-05 |
| noise 7 | 1.18904 | -0.00616141 | 0.0165906 | 3.46E-05 |

**Table 3.** The parameters estimation of $\alpha$ stable distribution of noise in Italy.

| noise | $\alpha$ | $\beta$ | $\delta$ | $\mu$ |
|-------|----------|---------|----------|-------|
| noise 1 | 1.75966 | 0.0282014 | 0.00760994 | -3.33E-05 |
| noise 2 | 1.78562 | 0.00118321 | 0.0078767 | 1.21E-05 |
| noise 3 | 1.75686 | 0.0565987 | 0.00792512 | -1.16E-04 |
| noise 4 | 1.7938 | -0.0211009 | 0.00790263 | 3.57E-05 |
| noise 5 | 1.74286 | 0.0265969 | 0.00835163 | -6.45E-05 |
| noise 6 | 1.77606 | -0.0156829 | 0.00890917 | 2.53E-05 |
| noise 7 | 1.85054 | -0.022285 | 0.0108844 | 4.48E-05 |
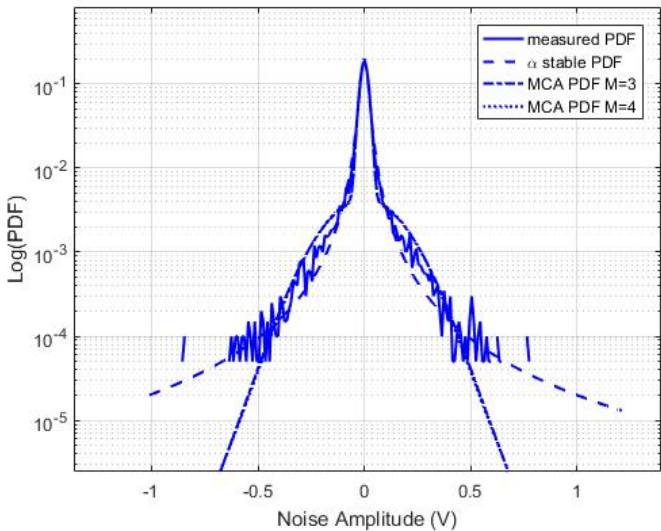


**Figure 11.** log(PDF) comparison of MCA , $\alpha$ stable model and measured noise data in China.

**Figure 12.** log(PDF) comparison of MCA, $\alpha$ stable model and measured noise data in Italy.
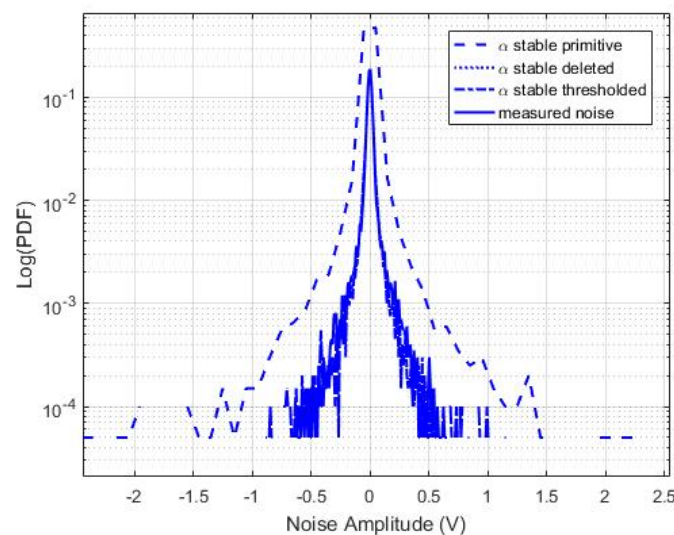


**Figure 13.** log(PDF) comparison of $\alpha$ stable primitive noise, $\alpha$ stable thresholded noise and measured noise data in China.

In Fig.11, it is shown that in the lower range of noise amplitude, both models can characterize impulsive noise well, while with the increase of the absolute of amplitude, it's noted that $\alpha$ stable distribution models better than MCA model. In Fig.12, with lower amplitude of noise measured in Italy, both models fit the measured noise well. When the amplitude increase, it shows that MCA model fits the tendency of impulsive noise better.

The primitive MCA model consists of infinite terms, and is truncated into finite terms when modeling, thus the noise generated based on MCA model will be limited in a reasonable range determined by the parameters $A$ and $\Gamma$. However, due to the asymptotic behavior of $\alpha$ stable distribution, the variance of stable distribution is infinite for $0 < \alpha < 2$. The amplitude of the noise generated by $\alpha$ stable distribution varies in a relatively large range, far exceeding the measured noise. From what have discussed above, it is possible to draw the conclusion that $\alpha$ stable distribution fits noise measured in China better, while MCA model fits noise measured in Italy better. Therefore,

when $\alpha$ stable distribution is applied to generate noise, the amplitude of the noise has to be restricted into a reasonable range. There are two ways to limit the generated noise, one is thresholding, and the other is deleting. In the former method of thresholding, thresholded noise $N_{th}(n)$ can be expressed as

$$N_{th}(n) = \begin{cases} N_\alpha(n) & if \quad |N_\alpha(n)| < T \\ T * sgn(N_\alpha(n)) & otherwise \end{cases} \tag{7}$$

where $sgn()$ denotes sign function, $N_\alpha(n)$ denotes noise generated by $\alpha$ stable distribution directly, and $T$ is the threshold. In the latter method of deleting, if the noise sample is over the threshold, it will be abandoned. To compare the performance of noise generation based on $\alpha$ stable distribution, $Log$(PDF) of the primitive noise generated by $\alpha$ stable distribution, the deleted one, the thresholded one and the measured noise are compared, as shown in Fig.13. We can see that with noise preprocessing, PDF fits well with the measured noise. Further, two methods of preprocessing originally generated noise make no difference and both fit well. Therefore, both thresholding and deleting methods can be adopted for generating impulsive noise.

## 5. Conclusions

In this paper, noise measured in China and Italy of 30-500kHz are compared based on basic characteristics in frequency and time domain using PSD and STFT. It is proved that noise measured in China is characterized by higher noise level in the whole frequency band, while the noise measured in Italy only has higher PSD in frequency lower than 50kHz, and can be regarded as white noise in the frequency band higher than 50kHz without considering NBI. Impulsive noise models are further built using MCA and $\alpha$ stable distribution model. The results show that noise measured in China can be fitted better by $\alpha$ stable distribution model, while noise measured in Italy can be modeled better based on MCA. In summary, power line channels in China is far more hostile than that in Italy due to high noise interferences.

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**Sample Availability:** Samples of the compounds ...... are available from the authors.