Characteristics of Low Voltage Distribution Networks in the European and FCC united Band and its Channel Capacity

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ABSTRACT

Communication over the low-voltage distribution networks is of great importance to the electrical engineering and networks engineering. The signal transmission characteristics and noise distributions over the distribution networks are the key factors to be considered in designing communication systems. In the past years, most previous works are concentrated on the European standard band (3~148.5kHz). In China, the legal frequency band for power line communications is 3~500kHz, covering the European band and the FCC band (100~450kHz). In this paper, the characteristics of signal transmission over 220V distribution networks and the characteristics of noise in the frequency range of 3~500kHz are investigated in detail. The work includes following parts. Firstly, the measurement procedure of transmission characteristics based on the S-parameters is discussed. Secondly, the measured results of transmission characteristics are described and modeled. Thirdly, the characteristics of noise are discussed and modeled. Fourthly, based on the measurements, the channel capacity is calculated using the water-filling method, and the result shows that the low-voltage distribution channel in the frequency range of 3~500kHz has the potentials to provide high transmission rate service for the subscribers of data communication.

I. INTRODUCTION

Communication over the low-voltage distribution networks is of great importance to the electrical engineering and networks engineering. In the past years, the interest in communications over the low voltage distribution networks has been raising continuously. The main reason is that the networks are almost universal in coverage and are easily accessed by standard commercial wall plugs, and the newly communication technology such as SSC (Spread Spectrum Carrier) and the OFDM (Orthogonal Frequency Division Multiplexing) provides good means for reliable communications. To design a good communication system over the low-voltage networks, the two key factors related the communication channel should be considered which are the signal transmission characteristics over the distribution networks and the noises on the networks. Most previous works related the channel characteristics are concentrated on the European standard band (3~148.5kHz) or other test bands for the feasibility studies [1]-[5].

In China, the legal frequency band for power line communications is 3 kHz~500kHz, that covers the European band and the FCC (Federal Communication Committee) band (100~450kHz). The electricity is supplied from a distribution transformer to householders and factories over the 220V/50Hz power lines in a tree structure, and the distance from the transformer to the users varies from several ten meters to several hundred meters. The loads of the users connected to the lines in parallel are rather dynamic and changing at all the time. To test the suitability of a technique in a given distribution network, the measurements and analysis of the channel characteristics on the network are needed. The primary purpose of this paper is to investigate the channel characteristics of the low-voltage distribution networks in frequency range of 3kHz~500kHz. The paper organized as follows. In section II, the measurement procedure of the transmission characteristics based on the S-parameters is discussed. In section III, the measured results of transmission
characteristics are described and modeled. In section IV, the characteristics of noise are discussed and a model is described. In section V, on the basis of the measurements, the channel capacity is analyzed using the water-filling method. In the end, some useful conclusions are summarized.

II. THE MEASUREMENT PROCEDURE OF THE TRANSMISSION CHARACTERISTICS

To measure the channel transmission characteristic of the low-voltage distribution networks, a measurement system using HP4395A is designed as Fig.1. The principle of measurement is described as follows.

![Fig.1 The transmission measurement system for low-voltage distribution networks](image)

A high frequency network with two ports is employed to equate the low-voltage distribution networks and the coupler as well as the high frequency transmission cables. The equivalent high frequency network is described by S parameters as Fig.2. The scattering equation of the equivalent high frequency network is as follows

\[
\begin{align*}
\frac{B}{R} &= \frac{c_2}{c_1} S_{21} \quad (2)
\end{align*}
\]

In practice, the transmission characteristics of the distribution networks are needed rather than that of the distribution networks plus the coupler network and high frequency transmission cable. For this purpose, the calibration is done within the working frequency range by shorting the distribution networks in Fig.2 (a), then the displayed curves on HP4395A measured by the principle shown in Fig.1 and Fig.2 belong to the ones of the distribution networks.

![Fig.2 S parameters of the transmission characteristics of distribution networks](image)

III. THE RESULTS OF MEASUREMENTS AND ANALYSIS OF THE TRANSMISSION CHARACTERISTICS

The distribution transformer is taken as the central node and the other nodes in different locations as remote nodes. A great number of tests between the central node and the remote nodes have been carried out. The measured curves of amplitude-frequency and group delay-frequency of the tested distribution networks are automatically recorded. The sweep frequency range is set to 3kHz~500kHz and the frequency resolution width (IF BW in HP4395A) is set to 1kHz.

Fig.3 and Fig.4 show two curves of the in-phase transmission characteristics of the tested network between the distribution transformer and a remote node (noted R3) approximately 100 meters away.
As shown in Fig.3, there is a downward trend of the amplitude of the transmission ratio with the frequency. In other words, the higher the frequency, the greater the signal attenuation. The fitted first-order exponential model of the transmission ratio is

$$20 \log_{10} |A(f, t_0)| = -45.81 + 45.13 \times \exp(-f / 208.35)$$

dB \quad (3)

where, $f$ is frequency in kHz. Except for the exponential downward trend, the amplitudes in some special frequencies exhibited sharp fall or rise, these amplitudes at the frequencies are transmission minimums and transmission maximums. The reasons for such transmission minimums and maximums are that passive loads in the distribution network resonated in above special frequencies or because of bifurcation of the loads, the multi-path signal propagation whose addition brought about the special phenomenon $^{[6][7]}$.

As shown in Fig.4, group delay-frequency is rather randomly, these non-constant group delays will cause the phase distortion so the error correcting encode should be used. The mean of the group delays is about $0.31 \mu S$. 

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As shown in Fig.6, group delay-frequency is rather randomly, these non-constant group delays will cause the phase distortion so the error correcting encode should be used. The mean of the group delays is about $0.31 \mu S$. 

Fig.3 Amplitude-frequency of the signal transmission (in-phase) over a distribution network

Fig.4 Group Delay-frequency of the signal transmission (in-phase) over a distribution network

Fig.5 Amplitude-frequency of signal transmission (cross-phase) over a distribution network

Fig.6 Group Delay-frequency of signal transmission (cross-phase) over a distribution network
The cross-phase transmission characteristics between the same two nodes are depicted in Fig. 5~Fig. 8. In general, the attenuation of cross-transmission is greater than the one of in-phase transmission, and the same is the group delay. Table I illustrates the comparison between the in-phase and cross-phase transmission.

Table I The comparison between in-phase and cross-phase transmission

<table>
<thead>
<tr>
<th></th>
<th>In-phase (C-C)</th>
<th>Cross-phase (A-C)</th>
<th>Cross-phase (B-C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average attenuation (dB)</td>
<td>-28.84</td>
<td>-45.17</td>
<td>-35.11</td>
</tr>
<tr>
<td>Average group delay (μs)</td>
<td>0.31</td>
<td>4.15</td>
<td>11.31</td>
</tr>
</tbody>
</table>

IV. THE CHARACTERISTICS OF NOISES

There are some different methods to catalogue the noises on the distribution line networks, such as Olaf G. Hooifén’s work [1]. The comprehensive kind of noise is the background noise. This kind of noise is caused by the all kinds of electrical apparatus, industry equipment and radio interference, etc. By the practical measurement, we find that the noise on the load side of the distribution transformer is most serious of all the noises. To establish the general idea of the characteristic of the noise in frequency domain and to compare to the works done by Olaf G. Hooifén, the frequency range of the spectrum analyzer is set 3kHz~500kHz with frequency resolution of 1kHz. A great number of noise measurements in different locations are carried out. Here we demonstrate two measurements in the distribution transformer and a remote node (R3).

The psd (power spectrum density) of the noise on the load side of the distribution transformer is shown in Fig. 9. It can be seen from the Fig. 9 that there is exponentially downward trend in the whole frequency range. The fitted model of the psd is

$$N(f) = -95.083 + 55.405 \times \exp(-f / 49.31) \quad [\text{dBm/Hz}]$$

(4)

where \( f \) is in kHz. The peaks in the Fig. 9 are the narrow-band noises discussed thoroughly by Olaf G. Hooifén[1]. Two obvious narrow-band noises are at (60.15kHz, -53.84dBm) and (108.99kHz, -57.96dBm).
The psd of the noise on a remote location (R3) is shown in Fig.11. There is no obvious downward or upward trend in the whole frequency range, the fitted model of the psd is

$$N(f) = -91.83 \ [\text{dBm/Hz}] \quad (5)$$

It means that the noise in this location is white noise. The further investigation shows that the amplitude distribution of the noise is AWGN (Additive White Gaussian Noise).

![Fig.10](image)

**Fig.10** The psd of the background noise on R3

### V. CHANNEL CAPACITY OF THE NETWORK

In general, the communication channel between any two nodes can be modeled as a linear time-variant system with channel transfer function $A(f, t)$ and additive noise $n(t)$ as illustrated in Fig.11.

![Fig.11](image)

**Fig.11** Model of low-voltage distribution networks channel

As discussed above, the communication channel from distribution transformer to a remote location (R3) is a Gaussian channel that is described by the channel transfer function $A(f, t)$ and psd of additive noise $n(t)$, the channel capacity $C$ can be calculated as

$$C = \int_{f_a}^{f_b} \frac{1}{2} \log \left( \frac{|A(f)|^2 B}{N(f)} \right) df \quad (6)$$

where $F_b$ is the range of $f$ for which $\frac{N(f)}{|A(f)|^2} < B$, and $B$ is the solution to

$$S = \int_{f \in F_b} S_n(f) df = \int_{f \in F_b} \left[ B - \frac{N(f)}{|A(f)|^2} \right] df \quad (7)$$

From equation (3) and (5), one may obtain

$$\frac{N(f)}{|A(f)|^2} = \frac{10^{-9.183}}{10^{-4.58 \times 4.513^{\exp(-f/208.35)}}} \ \text{W/kHz} \quad (8)$$

In China, the government regulation to the power line communication limits the signal power of transmitter no more than 3 W. According to this limitation, by solving equation (6)~(8) (see Fig.12 and Fig.13), the $B$ and the channel capacity $C$ can be determined

$$B = 8.493 \times 10^{-3} \ \text{W/kHz} \ , \ C = 3.514 \times 10^6 \ \text{bps}$$

![Fig.12](image)

**Fig.12** Water-filling method to solve the B

![Fig.13](image)

**Fig.13** Water-filling method to solve the C
VI. CONCLUSIONS

The signal transmission characteristics over the distribution networks and the noises on the networks are the key factors to be considered in designing communication systems over the distribution networks. In this paper, the characteristics of the signal transmission over the 220V distribution networks and the characteristics of noise in frequency range of 3~500kHz are investigated in detail. A novel procedure of transmission measurement based on the S-parameters is designed. Some of the measured results of the transmission and the noises are described and modeled. The channel capacity using the water-filling method is calculated. Based on the work shown above, the following useful conclusions can be summarized:

1. The signal attenuates almost exponentially with the frequencies in frequency range of 3~500kHz. The amplitude attenuation of cross-phase transmission is about 10dB larger than that of in-phase transmission at the same networks.

2. The group delay of the signal transmission is not constant, the channel equalization is needed to realize a reliable communication.

3. The noise level on the load side of distribution transformer is higher than that on other places and its power spectrum density attenuates almost exponentially with frequencies.

4. The noise on a common node of the distribution networks is almost AWGN.

5. The channel capacity is about 3.5Mbps per 100-meter distribution line, which means that the channel has the potentials to provide high-speed data communications.

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REFERENCES


