Analyses and Modeling of Power Line Channel Attenuation Characteristics for Low Voltage Access Network in China

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***Abstract*—This paper presents the measurement results of channel attenuation characteristics of low voltage access network in China. The measurement campaign was performed in typical urban and rural residential areas, which represents the underground cable and the overhead line topologies respectively. Both narrow-band (30-500 kHz) and broad-band (500 kHz-20 MHz) attenuations are investigated. Based on the extensive measurement results, statistical methods are used in the comparison of the average signal attenuation obtained in different areas, the attenuation profile with coupling mode match/mismatch, the attenuation dynamic range at different frequencies. These analyses may provide a comprehensive understanding of the representative channel attenuation characteristics for the access domain. Besides, the classical multipath model was used to model the broad-band (0.5-20 MHz) PLC channel after simplified. Results indicated that the simplified model covers the practical channel quite well.**

Keywords—PLC; attenuation; statistical analyses; modeling; low voltage; access network.

I. INTRODUCTION

Given the emerging services in smart grid, Power Line Communication (PLC) has become an attractive option for the data transmission system between the end users and the power provider especially in the access domain. In low voltage networks, PLC can be widely used for utility applications, such as Automatic Meter Reading (AMR), Advanced Metering Infrastructure (AMI), vehicle-to-grid communications and Demand Side Management (DSM) [1][2].

Channel characteristic is the most important factor which influences the communication system design, for the fact that any sensible communication systems are designed and optimized according to the particular characteristics of the channel. Lacking knowledge about power line channels has slowed down the system design and evaluation in the area of PLC [3]. Attenuation, noise, and impedance are the three critical parameters influencing PLC channel characteristics, and they are found to be unpredictable and variable with time, frequency and location [4]. A lot of efforts have been undertaken to characterize the power line channel [5]-[8]. Most of the recent results are related to the deterministic methods, which means the transfer function of a Transmission Line (TL) based channels can be deterministically calculated once the network topology is known.

Since signal attenuation characteristics are not well defined in practice because the complete electrical and impedance characteristics of power circuits are very complicated to measure and analyze, the influence of the attenuation characteristics may be understood by actual measurements and analyzed by statistical methods. The classical multipath model based on measurement is more practical in use. More attentions should be paid to the statistical characteristics [2]. Statistical methods are useful because “the variability of link topologies and wiring practices give rise to a stochastic aspect of wireline communications” [3]. The attenuation characteristics in average sense of different areas can be obtained and compared neglecting variations between individual paths. Since the cable types, network structures, and wiring methods of the low voltage access networks in China have remarkable differences when compared with those of abroad, there are already some papers on the signal transmission characteristics in the access networks of China [4][9][10]. However, none of the papers investigated the average signal attenuation characteristics in different areas. In this paper, a measurement campaign was performed in urban and rural residential areas and at different frequency bands to get an overall understanding of the low voltage channel attenuation characteristics in these areas. Both the underground and the overhead links that connect transformers with meter panels or House Access Points (HAPs) are mainly evaluated. Average signal attenuation characteristics in these typical urban and rural residential areas in China are compared. The impact of coupling mode match/mismatch, the attenuation dynamic range at different frequencies are also assessed.

The remainder of this paper is organized as follows. In Section II, the main factors influencing the attenuation characteristics are reviewed. In Section III, the measurement method and its procedures are described. Section IV shows the details about the field measurement sites. On that basis, the attenuation measurement results are presented and thoroughly analyzed in Section V. In section VI, the classical multipath model was simplified to model the PLC channel. Finally, section VII concludes this paper.

II. SIGNAL ATTENUATION CHARACTERISTICS

Power line is not a line designed for communications. Its signal attenuation characteristics are mainly affected by cable losses (including skin effect losses of cable conductors and dielectric losses of cable insulation materials), power splitting losses and reflection losses due to network branching or impedance mismatches. At particular frequencies, deep notches may be found due to frequency selective fading, which is mainly caused by multi-path signals with different phases overlapping constructively or destructively.

It is well accepted that signal attenuation becomes more significant when power lines are longer and frequencies are higher [5]. In [11], it was found out that the number of branches has a greater impact on signal attenuations than power line length does due to signal reflections or power splitting losses. Signal reflections caused by impedance mismatch make great contributions to the overall attenuation. Reflections often occurs at the connecting points of terminals or connecting points of power lines with different cable types where the characteristic impedances at each side of the point are mismatched. Moreover, cable losses show a growing trend with increasing frequency, which plays a major role in the overall attenuation at the frequencies above 10 MHz, while reflection and power splitting losses are predominant at low frequencies [12].

III. MEASUREMENT METHOD AND PROCEDURES

The schematic diagram of the measurement method is depicted in Fig. 1. A swept signal generator and the corresponding amplifier are used. The amplified signals are injected into the power line network at the transmitting side with the coupler A, and then acquired simultaneously at both the transmitting side and the receiving side with the coupler B. The transmitted and the received signals are recorded by a Digital Storage Oscilloscope (DSO) and the complex frequency response is obtained off-line on a laptop. The measurement equipments are shown in Fig. 2. The attenuation is calculated by Eq. (1).

$$A(f)_{dB} = 20\times \log\left(\frac{U_{\mathrm{r}}(f)}{U_{\mathrm{t}}(f)}\right) = S_{\mathrm{r}}(f) - S_{\mathrm{t}}(f) \tag{1}$$

$A(f)$ is the attenuation value in dB, $U_{\mathrm{r}}(f)$ is the measured voltage of the received signal at a certain frequency, and $U_{\mathrm{t}}(f)$ is the measured voltage of the transmitted signal at a certain frequency, $S_{\mathrm{r}}(f)$ and $S_{\mathrm{t}}(f)$ represents the signal strength of the received signal and the transmitted signal respectively in dB.

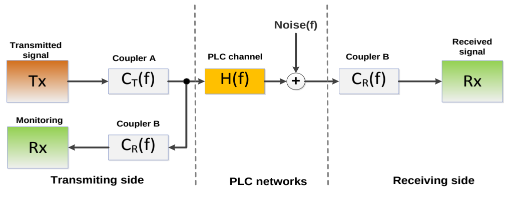

Fig. 1 Schematic diagram of the attenuation measurement method

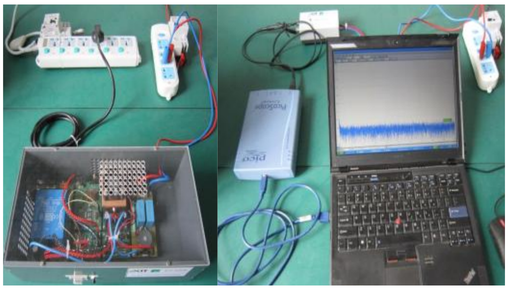

Fig. 2 Measurement equipments

The measurement procedures are listed as follows：

(1)Set the parameters of the measurement software, for example, the sampling rate for the narrow-band (30-500 kHz)/broad-band (0.5-20 MHz) signals are 1 MHz and 40 MHz respectively.

(2)Connect the swept signal generator with the coupler A, and the swept–frequency signals are injected into the power line via the coupler A and collected via the coupler B.

(3)The swept-frequency signals are received by a data collector (PicoScope) via another coupler B connected to the receiving end simultaneously, and the PicoScope is connected to a laptop via USB.

(4)After the above steps, the strengths of transmitting/receiving signals are obtained, and the attenuation of the measured path can be calculated by Eq. (1).

Generally, in three phase supply networks, there exist several ways to couple PLC equipments at the transformer substation (. /. means parallel connection):

- All conductors involved (A/B/C vs. Neutral)
- All phases involved (e.g. A/C vs. B)
- Arbitrary single Phase to Neutral (e.g. B vs. Neutral)
- Two phases (e.g. A vs. C)

In this paper, the third option, arbitrary single Phase to Neutral, is mainly investigated.

IV. MEASUREMENT SITES

The measurement campaign was performed in the selected low voltage access network Test Site (TS) in China, such as typical urban residential area and typical rural residential area.

A. *Urban residential area*

Fig. 3 illustrates the network topology with three buildings 2#, 26# and 35# chosen for the urban residential area in Handan, Hebei Province (TS 1). Separate underground cable links the transformer with the HAP of each building. The length of the power cable is about 50 m, 250 m and 350 m respectively. Building 2# and 26# have 3 and 6 blocks respectively, and each block has 6 floors and a meter panel with 12 single phase meters. Building 35# has 1 block of 8 floors and 1 meter panel with 16 single phase meters. The meter panel is about 5-20 m away from the HAP [13]. The swept-frequency signals are injected at the feeder of the transformer and received at HAPs or meter panels of buildings 2#/26#/35# respectively.

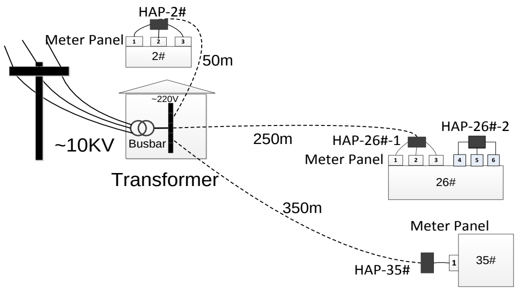

Fig. 3 The network topology of the urban residential area measurement site

B. *Rural residential area*

Fig. 4 illustrates the network topology of rural residential area in Xicheng Village, Zhejiang Province (TS 2). The overhead line links the transformer with single phase meter panels or three phase meter panels of each house. The lengths of the power line sections varies from 2 m to 20 m. The swept-frequency signals are injected at the feeder of the transformer and received at meter panels of 0#/1#/2# respectively.

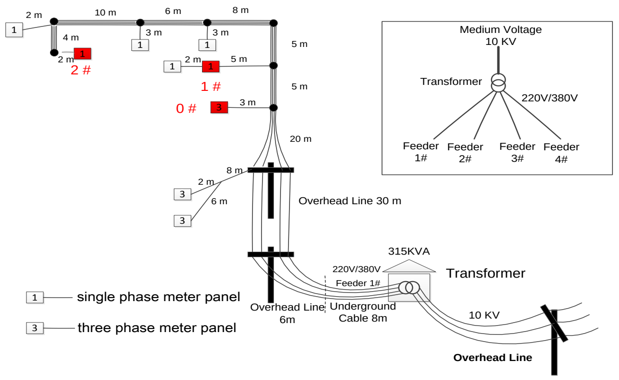

Fig. 4 The network topology of the rural residential area measurement site

V. Measurement Results And Analyses

A. *Comparison of the average attenuation in urban and rural residential area*

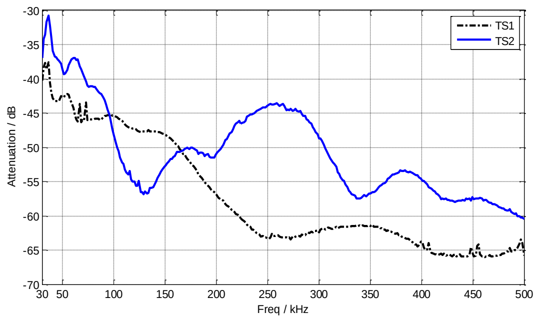

Fig. 5 Comparison of the average attenuation in TS 1 and TS 2

The measured attenuation characteristic of a link is composed of various attenuation values at discrete frequencies. The average attenuation of different links at each frequency is calculated to get the average attenuation profile varying with frequency. The measured links include all kinds of single phase coupling modes (A vs. Neutral, B vs. Neutral, C vs. Neutral) and different receiving ends. In other words, the average attenuations of one residential area are calculated neglecting the coupling mode and the length of a link. The narrow-band (30-500 kHz) attenuation characteristics in average sense of different residential areas are compared in Fig. 5, where the difference between individual links is neglected. The corresponding network topologies are shown in Fig. 3 and Fig. 4 respectively.

It can be seen that the average attenuation measured in TS 1 ranges from -35 dB to -65 dB, increasing with frequency between 30-250 kHz and remaining relatively flat between 250-500 kHz. The attenuation profile of TS 2 exhibits some deep notches lying at 130 kHz and 340 kHz and a peak at 250 kHz, which ranges from -30 dB to -60 dB.

In urban areas, residential buildings are often supplied by dedicated feeder cables without branching. The attenuation profile of this kind of area is relatively smooth as shown in TS 1. While in rural areas of China, high density of scattered houses leads to numerous feeder taps from the main feeder cable, especially in row house estates where house supplies (Tap of a feeder to supply a house) have equal lengths, may causing strong frequency selective attenuation due to signal reflections at impedance discontinuities, shown in results from TS 2 [12]. Besides, the overhead lines in TS 2 has less attenuation compared with the underground cables in TS 1.

B. *Impact of coupling mode match/mismatch*

To evaluate the impact of coupling mode on attenuations, the measured results in TS 1 are used as an example. The signals are sent at the transformer and received at the HAP of 26# of TS1 using the single phase coupling mode. Measurements including coupling mode match (e.g. AN-AN) and mismatch (e.g. AN-BN) are conducted respectively between the transmitting and the receiving end. The impact of coupling mode match/mismatch on the mean attenuation profile is compared in Fig. 6 (narrow-band between 30-500 kHz) and Fig. 7 (broad-band between 0.5-20 MHz).

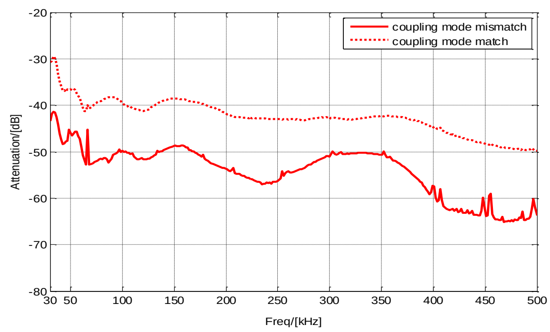

Fig. 6 Comparison of mean attenuation profile with coupling mode match/mismatch between transmitting and receiving end (narrow-band)

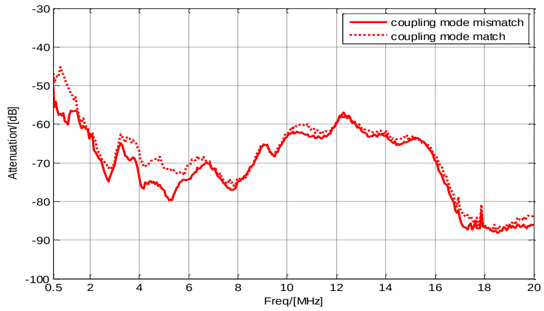

Fig. 7 Comparison of mean attenuation profile with coupling mode match/mismatch between transmitting and receiving end (broad-band)

From the results it's found that the variance in attenuation profile with coupling mode match/mismatch ranges from 5 dB to 15 dB in narrow-band case, while there is nearly no difference in broad-band case. Due to the shorter wavelength of broad-band signal, the signals are more likely to radiate out from the power line circuit, and coupled to the other phase-neutral circuits, causing the attenuation profile of coupling mode match/mismatch tend to be the same.

C. *Comparison of attenuation dynamic range at different frequencies*

The attenuation dynamic range at each frequency is defined as the difference between its maximum and minimum attenuation values based on the measured statistics. The dynamic range of all attenuation profiles measured at 26# of TS 1 are compared in Fig. 8 and Fig. 9 in different frequency bands.

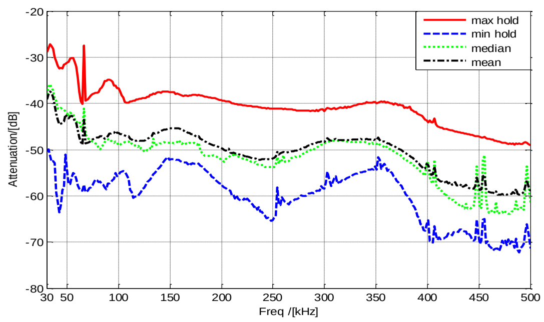

Fig. 8 Dynamic range of attenuation profiles measured at 26# (narrow-band)

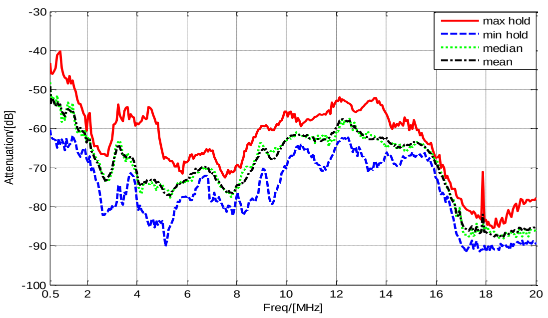

Fig. 9 Dynamic range of attenuation profiles measured in 26# (broad-band)

It shows that the dynamic range of attenuation profiles in narrow-band has a larger spread than broad-band case. The average attenuation of narrow-band channel ranges from -40 dB to -60 dB while the average attenuation of broad-band channel ranges from -50 dB to -85 dB, approaching the noise floor at high frequencies. Besides, the attenuation values at 500 kHz in Fig. 8 and Fig. 9 are different, this variance is mainly results from the time-varying feature of the channel. Although the results of narrow-band and broad-band are not acquired simultaneously, the attenuation dynamic range obtained based on several test results reflects the channel attenuation time variability to a certain extent.

VI. CHANNEL MODELING

The PLC channel is difficult to model due to different transmission mediums and network topologies. Every part of the transmission line has its own channel transfer function from a communications point of view. Many authors have been working for a better understanding of the properties of the PLC channel, there are divided into two groups: the bottom-up approaches and the top-down approaches. The former approaches describe the behavior of a network by a large number of distributed components (cables, joints, connected devices)[2]. It is hard to determine all the parameters in practice. In contrast to it, the top-down strategy treat the channel as a black box and describe its transfer characteristics by a frequency response with a few parameters. The parameters are obtained from channel measurements. In this paper, the multipath model based on the top-down strategy was simplified to model the PLC channel. According to this model, the transfer function is[5]:

$$H(f)=\sum_{i=1}^{N} g_i \cdot e^{-(a_0+a_1 f^k)d_i} \cdot e^{-j2\pi f(d_i/v_p)} \tag{2}$$

Where g_i representing the product of the reflection and transmission factors along the path, $\alpha(f)=a_0+a_1 f^k$ is the attenuation factor and d_i is the path length, v_p is velocity of propagation along the power line cable, and N is the number of non-negligible paths. The accuracy of the model strongly depends on N and on the exact parameter settings, for simulation purposes, the $\alpha(f)$ can be replaced with $a_1 f$ to simplify the calculation. In this way, the general impairments of the channel are obtained and unimportant details are hided, this method works effective in practice. The average attenuation profile varying with frequency (0.5-20 MHz) in 26 # of TS 1 are used as an example, the parameters g_i, d_i, a_0 were estimated with a least-squares fitting algorithm after N was fixed. From simulation results in Fig. 10, it is found that N=9 is enough to describe the general properties of channel attenuation. The amplitude response of the model and measurement result exhibit some differences, especially at the locations of the sharp notches. However, the amplitude response is still covered quite well by the simplified model(N=9).

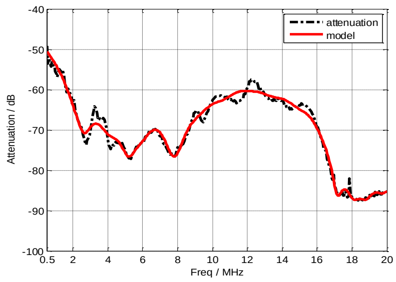

Fig. 10 Average attenuation profile of TS1 and simulation with N =9 paths

TABLE I. PARAMETERS OF THE 9 PATH MODEL

Attenuation parameters					
$k=1, a_0=0, a_1=6.6\cdot 10^{-11} m/s$					
Path parameters					
i	***g*i**	***d*i/m**	***i***	***g*i**	***d*i/m**
1	0.00045	318	**6**	0.000041	267
2	0.00013	359	**7**	0.00054	334
3	0.000018	420	**8**	0.000015	477
4	-0.0028	6914	**9**	0.00021	351
5	0.00011	302			

The accuracy of the modeling is evaluated by the RMSE between model and attenuation measurement result, the RMSEs of 2-path model to 9-path model are calculated and plotted in Fig. 11, indicating how the accuracy varies along the number of paths.

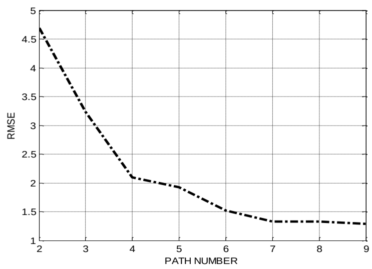

Fig. 11 RMSEs of different models

VII. CONCLUSIONS

In this paper, channel attenuation characteristics of typical low voltage underground/overhead access networks in China are measured. Measurement methods and numerous results are also presented and analyzed.

By comparing the average attenuation between urban and rural residential areas, it’s found that the attenuation versus frequency profile in urban area is much flat than that of rural area possibly due to no (or less) branches along the measurement path. When using single phase coupling mode to send and receive signals, the impact of coupling mode match/mismatch on attenuation profiles is more apparent in narrow-band case (5-15 dB) than in broad-band case due to the shorter wavelength of broad-band signal. The attenuation dynamic range in narrow band has a larger spread (15-25 dB) than broad-band case (5-20 dB), because broad-band signal is more easily coupled to the other phase-neutral circuits, showing less variance between different phase-neutral circuits.

The simulation results indicated that the general impairments of the channel can be covered by simplified multipath model with less than 9 paths, which is practical in PLC-system performance evaluation and comparison.

ACKNOWLEDGEMENT

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