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Analysis and Modeling of Noise on 22.9-kV Underground Power Distribution Cable for Broadband Power Line Communication

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Abstract

This paper reported the measurements and modeling of noise on the 22.9kV Medium-Voltage (MV) underground power distribution cable for Broadband Power Line Communication (BPLC). The proposed measurement system was composed of inductive coupler and Digital Phosphor Oscilloscope (DPO). The empirical noise data with the measurement system was obtained from thirty-two pad mounted transformers in the test field located in Choji area of Ansan city. After conducting analysis of noise characteristics in time and frequency domain, the noise model are presented. In order to analyze the noise in frequency domain, Power Spectral Density (PSD) was computed with empirical data using Welch's method. The model of the power line noise at each frequency carried out using Cumulative Probability Distribution (CPD) of computed noise power. It compared with common Cumulative Distribution Function (CDF) of Nakagami-m distribution, Gaussian distribution, Gamma distribution. Below 20MHz frequency range, gamma distribution was fitted with the CPD. Nakagami-m distribution provides a good fitting to the noise CPD above 20MHz frequency range.

Keywords: *Noise Modeling, Noise measurement, Medium-Voltage Underground Power Distribution Line, Broadband Power Line Communication, Cumulative Probability Distribution*

1. Introduction

The underground power distribution cable is the most important communication media as a backbone network for the BPLC. Formerly, cable network or fiber optics is used for the purpose of backbone network because of cost-effective Power Line Communication (PLC) technology. Until now, a number of studies of PLC were performed by several researchers for Low-Voltage (LV) and In-House PLC. However, recently MV power line has been considered as a backbone network of whole power line network. Although, a group of studies show in some detail information of the impedance, transmission properties and noise characteristics of the MV power line network, the characteristics of 22.9-kV MV underground power line is not so well known[1,7].

Detailed channel parameters such as noise, frequency, signal attenuation, impedance and location are required for high performance PLC systems. Noise characteristic of the PLC channel play an important role to determine performance of PLC between above parameters [2]. Accurate noise model is required to realize high bit rate transmission of the BPLC. The noise model in 10-kV MV, LV and in-house was done by a lot of researchers. However, the model of the noise on 22.9kV MV power line is rarely regarded in the literature. This paper only considered noise on 22.9kV MV power line which is critical factor in performance of PLC systems for BPLC.

To model the noise of MV power line, this paper presents measurements results of the 22.9kV MV underground power line noise based on empirical noise data obtained from thirty-two pad mounted transformers in the test field of a suburb of Ansan city near Seoul, Korea. After conducting careful analysis with empirical data in time and frequency domain, modeling of the data at each frequency was also carried out for accurate noise model.

Section II presents measurement environment and system for the noise characteristics. In Section III, results of measured data in time domain and computed PSD are discussed. The appropriate noise model at each frequency is described in Section IV. The concluding remark is given in Section V.

2. Measurements

2.1. Measurement environment

The test field using underground 22.9kV MV power distribution line has been constructed by Korea Electrotechnology Research Institute (KERI) in Choji area located in Ansan city, Korea. The measurements were conducted at 3-phase pad mounted transformers of thirty-two sites, Poonglim - T02 (Transformer number), T03, T04, T05, T06, T07, T08, T09, T18, T19, T20, T21, T22, T23, T24, T25, T26, T27, T28, T30, T31, T32, T33, T40, T42, T43, T44, T45, T46, T47, T52 and T53 located in 1B/L and 11B/L of the test field as shown in Figure 1.

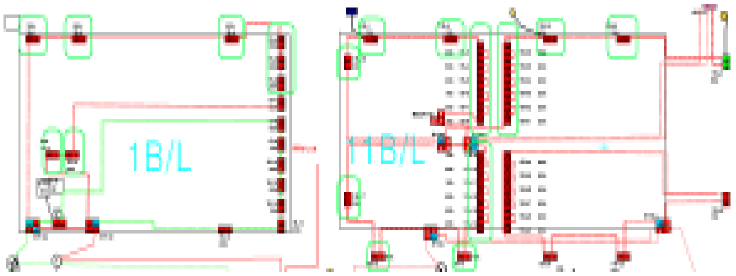


Figure 1. Location of the 3-phase pad mounted transformers

2.2. Measurement setup

Figure 2 describes composed noise measurement system in the test field. The data was obtained by inductive coupler and DPO of the system. The inductive coupling unit was installed with phase A of the 3-phase transformer and connected with the oscilloscope.

In the noise measurements, we used a TEKTRONICS DPO3032 to record empirical noise data in time domain with USB memory sticks. A sample rate 100 mega samples per second was chosen for spectral analysis to 50MHz frequency range by Shannon sampling theorem.

In order to overcome harsh environment of measurements and prevent high-voltage, MATTRON MTR-ICU-H58 (see Figure 3) inductive coupler was used in the system. The inductive coupler employed a principle of magnetic induction easily connected to outer of power line different from capacitive coupler. Since high current flows through the MV underground power line, a magnetic core of inductive coupler should have high permeability and saturation current characteristic. The coupler employed for the measurement system has highest permeability, lowest power loss and the magnetic properties without magnetic saturation on the subterranean power line transferred high current of 300A[3].

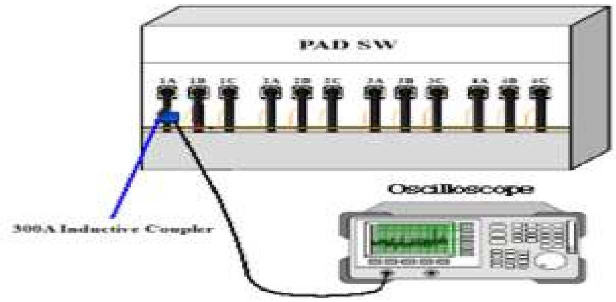


Figure 2. Measurement system

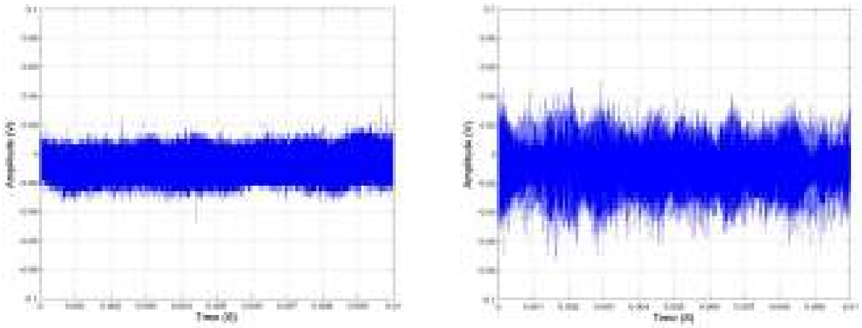
Figure 3. A photograph of the inductive coupler of the system

3. Experimental results

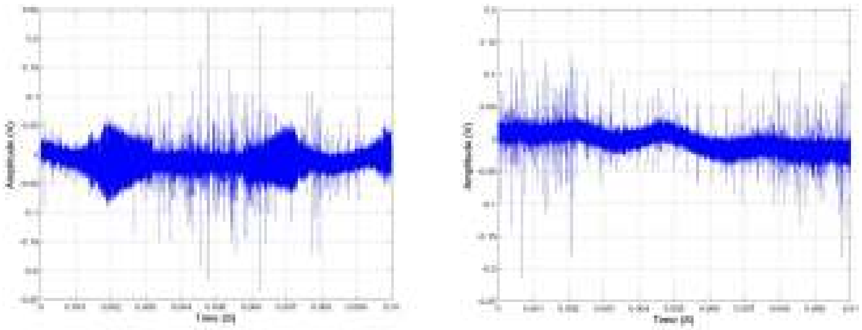
3.1. Characteristics of the noise

The noise in LV power line channel can be separated into five classes listed as following [4]:

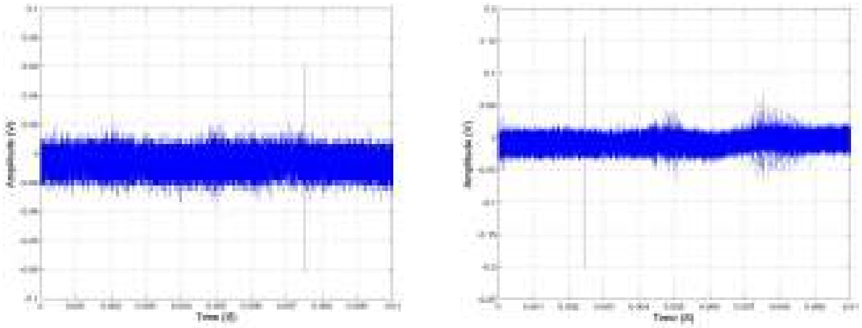
- Colored background noise has a comparatively low PSD in the PLC frequency range. The noise is mainly caused by summation of numerous noise sources and physical characteristics of the power line.
- Narrow band noise is mostly modulated sinusoidal signals. The noise is mainly caused by medium, short wave broadcasting and communication signals.
- Periodic impulsive noise asynchronous to the mains frequency appeared a shape of simple line in frequency domain. The noise mainly caused by switching of power supplies.
- Periodic impulsive noise synchronous to the mains frequency is mainly caused by switching actions of several electrical elements in many appliances.
- Asynchronous impulsive noise is mainly caused by switching transients in the power network.



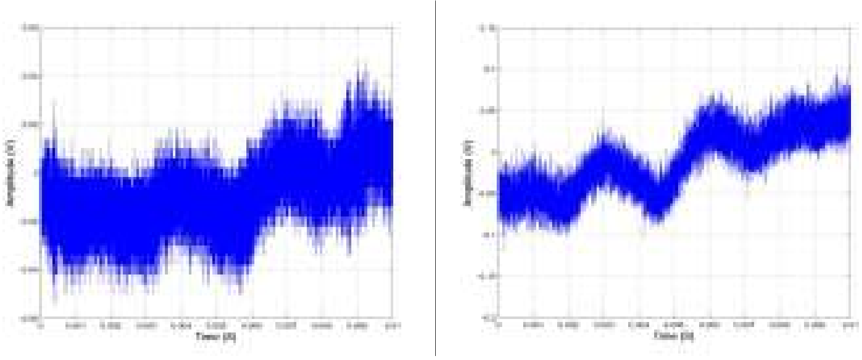
(a) T02 (b) T05



(c) T23 (d) T25



(e) T28 (f) T30



(g) T43 (h) T52

Figure 4. Representative noise graphs in time domain

Since colored background noise and narrow band noise vary slowly over time, they can be regarded as background noise. The latter three types have rapid time-varying properties, so that they can be summarized as impulsive noise [4].

The classification of noise in LV power line can be adopted to represent characteristics of noise of MV power line. However, since wireless disturbances impact LV power line network heavily, narrowband noise amplitude of MV power line with the pad mounted transformers is less than of LV power line. Impulsive noise amplitude mainly related with appliance noise were also lower than LV power line, because MV power line was not directly connected with house appliances.

As stated above, the measurements were conducted in thirty-two pad mounted transformers in the test field. The record of each measurement has a length of 0.01s, so that 1 million samples of each measurement were obtained. The thirty-two graphs can be classified into four representative types following its line shape (see Figure 4). Two figures were presented each type of noise as shown in Figure 4. The results show the MV power line noise can be considered sum of the background noise and the impulsive noises.

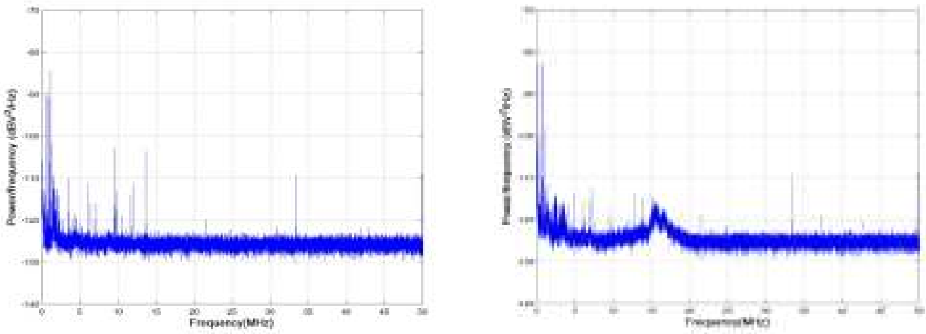
The noise graphs of Figure 4 (a), (b), (g), (h) stationary remain over measurement period, so that they can be regard as a background noise. Figure 4 (c), (d), (e), (f) show impulsive noise comprised background noise on MV power line. Table 1 shows computed mean and variance values of noise amplitude at each transformer to give noise level on the MV power line. The noise data-sets have mean value a range of -12mV ~ -1mV except for T18 which has a mean value of 10.90mV and high variance with T52.

Table 1. Mean and vriance values of noise data at each transformer

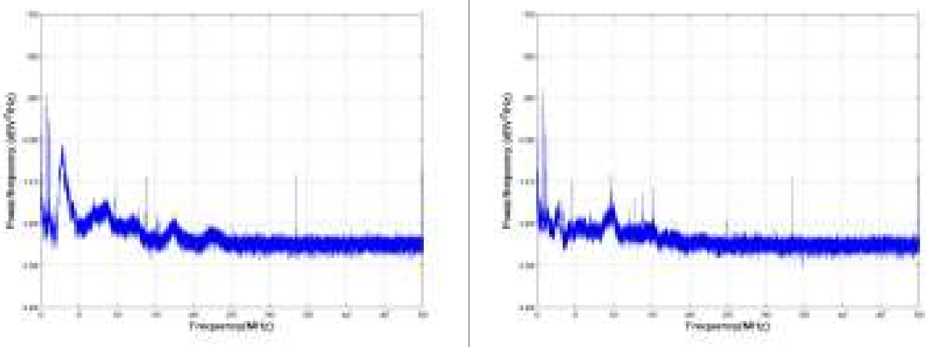
Transformer	Mean(mV)	Variance(mV^2)	Transformer	Mean(mV)	Variance(mV^2)
T02	-5.87	35.5	T26	-7.25	139.6
T03	-6.06	25.0	T27	-8.73	193.2
T04	-6.28	57.9	T28	-4.87	25.6
T05	-7.48	128.4	T30	-5.93	66.3
T06	-6.18	129.6	T31	-5.38	37.3
T07	-5.37	83.5	T32	-6.48	36.0
T08	-5.22	56.1	T33	-3.77	59.4
T09	-4.34	68.2	T40	-4.58	287.4
T18	10.90	954.2	T42	-7.81	175.0
T19	-5.21	50.0	T43	-8.42	142.8
T20	-8.52	113.3	T44	-9.99	114.0
T21	-8.41	57.2	T45	-5.40	89.2
T22	-1.53	60.4	T46	-5.38	56.4
T23	-9.21	95.5	T47	-8.18	54.2
T24	-6.83	92.1	T52	-11.68	1348.8
T25	--3.43	149.1	T53	-10.42	100.8

3.2. Spectral analysis

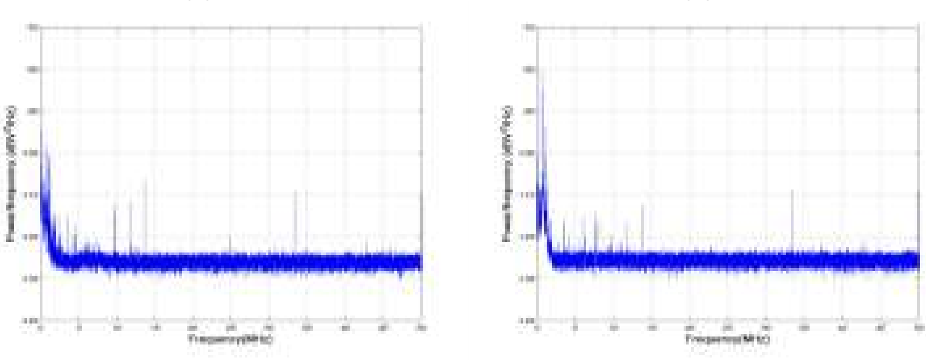
In order to assess impact of the noise on communication channel with limited bandwidth, the spectral analysis of the noise data is a better approach [4]. Also, for more effective modeling of the noise, the PSD of the noise is considered. The spectral estimation was carried out using Welch's method from the thirty-two noise data-sets [5].



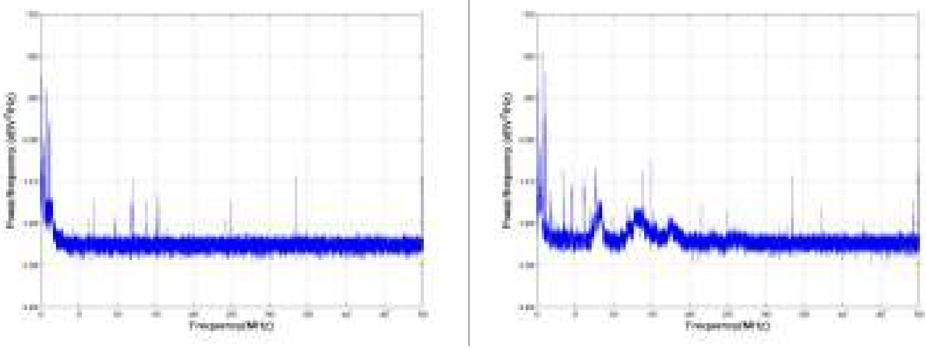
(a) T02 (b) T05



(c) T23 (d) T25



(e) T28 (f) T30



(g) T43 (h) T52

Figure 5. Computed noise PSD of empirical data at each transformer

Figure 5 shows computed PSD from the empirical noise data at the T02, T05, T23, T25, T28, T30, T43, and T52 the same as graphs of Figure 4. The PSD of background noise is shown in Figure 5(a). The noise data of T05 represent background noise comprised narrow band disturbances as shown in Figure 4(b) and 5(b). The periodic impulsive noise asynchronous or synchronous to the mains frequency has a relatively high PSD value (see Figure 5(c) and 5(d)). A noise data of the T28 and T30 (see Figure 4(e) and 4(f)) describes a simple impulsive noise characteristic in time domain, however, in frequency domain it can be regarded as the background noise (see Figure 5(e) and 5(f)). Figure 5(g) and 5(h) shows background noise included narrowband noise. This type of noise has high PSD value in low frequency range. From the figure 5, there are more disturbances in the MV power line network which affect low frequency range below 15 MHz such as short wave radios. Average PSD value of the noise PSD from the thirty-two transformers was presented in Figure 6.

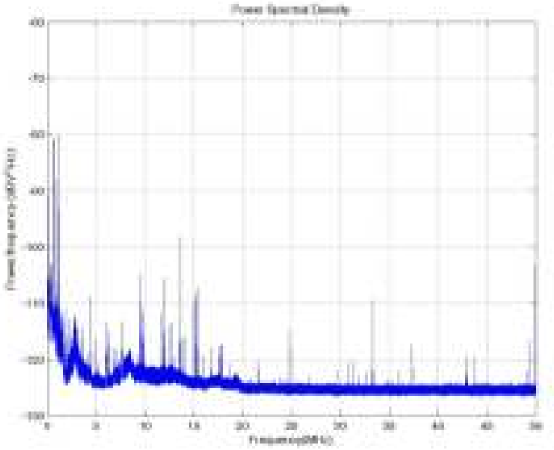
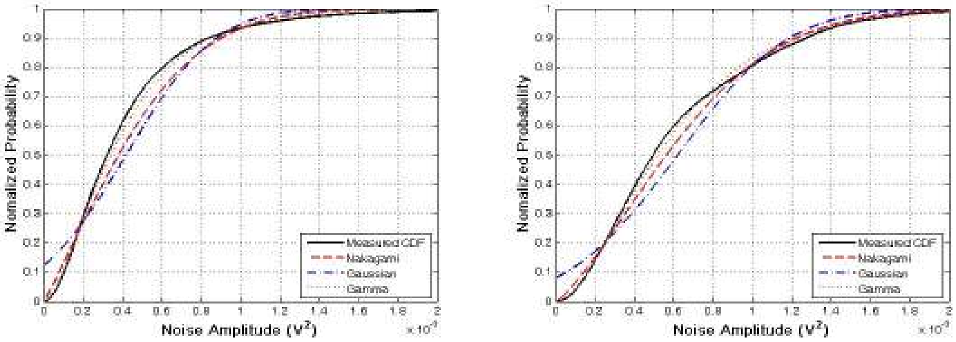


Figure 6. Average PSD value of thirty-two transformers

4. Noise modeling and verification

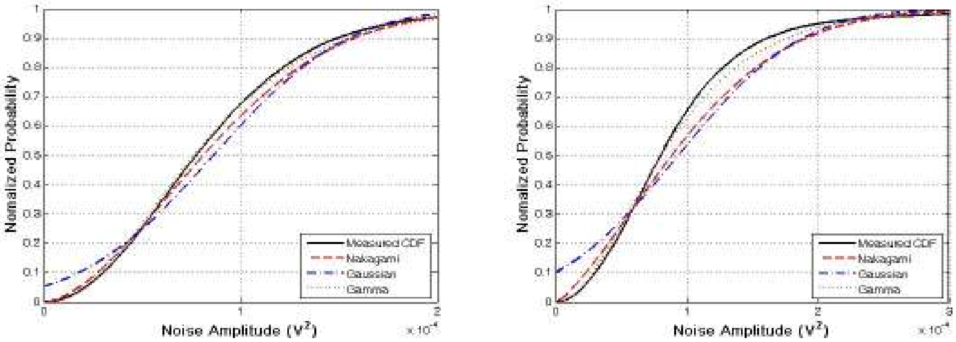
The appropriate noise model is required to design the PLC network. Many articles regarding some modeling techniques of the LV power line noise in frequency domain and time domain were presented in the literature [4,6,7,8]. In order to obtain average noise PSD, the modeling method in frequency domain was used in the literature. Average noise PSD usually was modeled with exponential function and Gaussian function. However it does not represent any noise information comprised random behavior of the noise at each frequency [7]. Hence, in this section of this paper represents the noise model on MV power line at each frequency.

To model of the noise on MV power line at each frequency the CPD was computed at each frequency. Computed CPD from empirical data is compared with some well known CDFs, Nakagami-m distribution [6], Gaussian distribution [8] and Gamma distribution [7]. Figure 7 shows the comparison between the calculated CPD and the common CDFs at each frequency. Since the CPD at each frequency was fitted into Gamma distribution below 20MHz of frequency range and Nakagami-m distribution above 20MHz range (see Figure 7), a certain frequency of 200kHz, 1MHz, 5MHz, 10MHz, 15MHz, 20MHz, 25MHz, and 30MHz were chosen to accurately compare with the CDFs as shown in Figure 5.



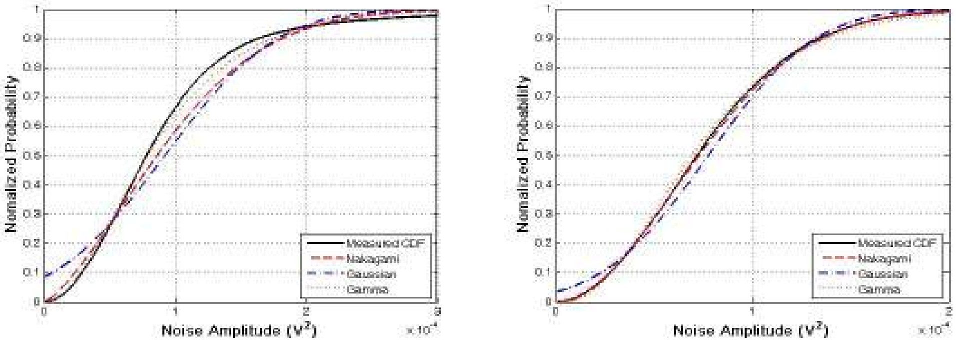
(a) 200 KHz

(b) 1 MHz



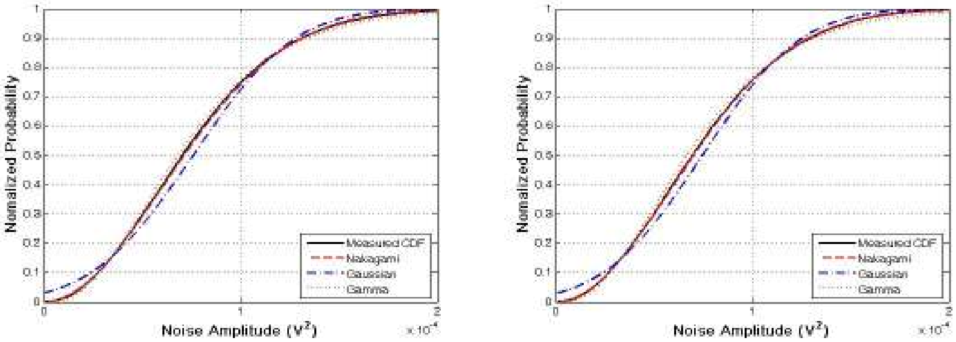
(c) 5MHz

(d) 10MHz



(e) 15MHz

(f) 20MHz



(g) 25MHz

(h) 30MHz

Figure 7. Comparison of the calculated CPD and the CDFs at each frequency

The Nakagami-m PDF can be written as

$$p(r|m,\Omega) = \frac{2m^m}{\Gamma(m)\Omega^m} r^{2m-1} e^{\frac{-mr^2}{\Omega}}. \quad (1)$$

, where m is defined as the ratio of moments $m = E^2[X^2]/VAR[X^2]$, Ω is the mean power of the random variable r, $\Gamma(\cdot)$ is the Gamma function. And the Gamma CDF is as the following:

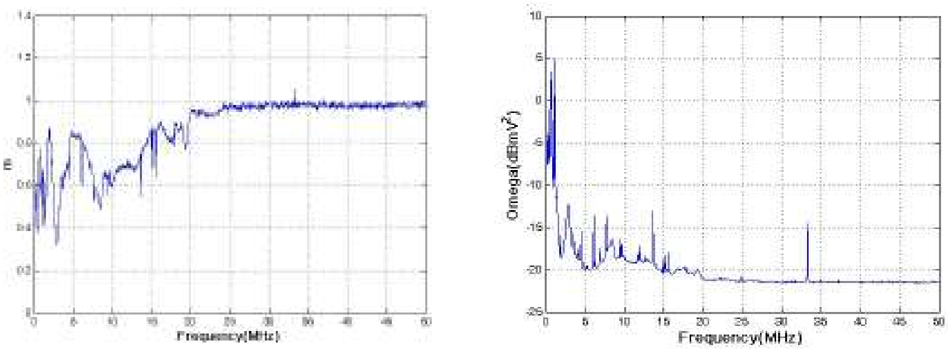
$$F(r|a,b) = \frac{1}{b^a\Gamma(a)} \int_0^x t^{a-1} e^{-t/b}\, dt. \quad (2)$$

, where a is a=m and b is $b=\Omega/m$.

The computed CPD at 200kHz, 1MHz, 5MHz, 10MHz, and 15MHz are fitted with Gamma CDF as shown in Figure 7 (a), (b), (c), (d), and (e) respectively. The Nakagami-m distribution provides excellent fitting into the CPD at 20MHz, 25MHz and 30MHz (see Figure 7 (f), (g), and (h)). The value of m and Ω for Nakagami-m and Gamma CDF as shown in Table 2. Variation at each frequency of the value of m and Ω was shown in Figure 8(a) and 8(b) respectively.

Table 2. The m and Ω value at certain frequencies

Frequency	m	Ω
200kHz	0.52	3.02×10^{-7}
1MHz	0.63	5.82×10^{-7}
5MHz	0.81	1.03×10^{-8}
10MHz	0.64	1.04×10^{-8}
15MHz	0.68	1.31×10^{-8}
20MHz	0.82	1.32×10^{-8}
25MHz	0.98	1.32×10^{-8}
30MHz	0.99	1.31×10^{-8}



(a) m (b) Ω

Figure 8. The m and Ω profiles of PLC frequency range

The Pearson's chi-squared test was used to evaluate difference between the observed CPD and the theoretical CDFs. Usually, the chi-squared value of the test-statistic can be written as

$$\mathrm{X}^2 = \sum_{i=1}^{n} \frac{(\mathrm{O_i} - \mathrm{E_i})^2}{\mathrm{E_i}} \tag{3}$$

, where n is the number of divided intervals, $\mathrm{O_i}$ is the empirical chi-squared value, $\mathrm{E_i}$ is the theoretical value in the ith interval. In order to calculate the test-statistic value, data sample was divided into ten intervals. Since the CDFs have two unknown parameters, degree of freedom can be presented 7 (=10-2-1). Therefore, computed the standard value X^2 is $\mathrm{X}^2_{1-\alpha} = \mathrm{X}^2_{0.99} = 18.48$, when the α is α=1%. The standard value of X^2 compared to the calculated X^2 value to find goodness of fit in the CDFs and CPDs.

By performing the chi-squared test, assumed the Gamma distribution and the Nakagami-m distribution was accepted for modeling in below 20MHz and above 20MHz, respectively. The CPD of 20MHz frequency range was also fitted with the Nakagami-m CDF. The value of X^2 of the Gamma distribution is 4.57 at 200kHz, 4.81 at 1MHz, 0.32 at 5MHz, 0.51 at 10MHz, and 1.08 at 15MHz. The computed chi-squared value of the nakagami-m distribution is 0.06 at 20MHz, 0.09 at 25MHz, and 0.03 at 30MHz. Under the standard value of $\mathrm{X}^2_{0.99}$ =18.48, the Gamma distribution and Nakagami-m distribution is accepted to the noise model at certain frequency range. Upper 20MHz frequency range, chi-squared values of Gamma distribution with the CPD were also satisfied the chi-squared condition. However, the value of Nakagami-m distribution is lower than the value of Gamma distribution. Hence the Nakagami-m distribution was accepted to appropriate noise model above 20Mhz frequency range.

5. Conclusion

Recently, the MV power line has received tremendous attention as a backbone network of entire PLC network to replace fiber optics and cable network. In order to implement great communication system, specific channel characteristics are required including noise characteristics. The noise characteristics of the LV power line and In-house power line are well known. However, information of the MV power line is not enough to realize the PLC network with MV power line.

Therefore, this paper proposed the measurements and modeling of noise on the 22.9-kV Medium-Voltage (MV) underground power distribution cable for Broadband Power Line Communication (BPLC). The proposed measurement system was composed of inductive coupler and Digital Phosphor Oscilloscope. The measurements were carried out in the test field located in Choji area of a suburb of Ansan city near Seoul, Korea. The time domain analysis of the measured noise was conducted, also frequency domain analysis of the noise data was performed with PSD using Welch's method. Based on the empirical noise data, the CPDs were calculated at each frequency for the model of noise. And then, common CDFs were compared with the CPD at each frequency. The Gamma distribution was fitted into the CPD below 20MHz frequency range. Above the 20MHz, Nakagami-m distribution was accepted to the noise model. These results are verified with Pearson's chi-squared test to determine accurate noise model. It is different results of the noise model on LV power line which has a model of Nakagami-m distribution in entire PLC frequency band.

Acknowledgement

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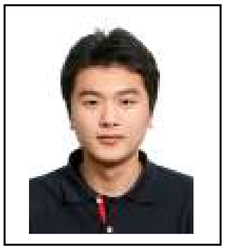

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Jae-Jo Lee was born in Chang-won, Korea, in 1967. He received the B.S. degree in physicsand the M.S. degree in electronic engineering from Kyung Hee University, Seoul, Korea, in 1990, 1992, respectively, and the Ph.D. degree in electronics engineering in 2005. In 1992, he joined the Korea Electrotechnology Research Institute (KERI), Geonggi-do, Korea, where he worked on power telecommunication networks as a Researcher. From 1999 to 2004, he was involved in the development of power-line communication network technology as a Senior Member of Technical Staff. Since October 2005, he has been a Project Manager of the ubiquitous power-line communication networks development project. His research interests include power line communications, home networking, and network management systems. Dr. Lee is a member of the Korean Institute of Electrical Engineers (KIEE) and the Korean Institute of Communication Sciences (KICS). He is a Principal Researcher in Power Telecommunication Network Research Group of KERI.

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