Transmission degradation in the frequency band of Power Line Communication caused by Resonant circuit consisting of surge protective devices

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Abstract: - In the paper of WSEAS Dec.2007 [1], we proposed that Surge Protection Devices, such as varistor type SPDs, degraded the transmission rate of Power line communication modem. By the research after that, not only the capacitance of the varistor but also the inductance of the varistor and wiring of SPD causes resonance. In this paper, the relationship among capacitance, maximum current, the size of disk and varistor- voltage is analyzed. The inductance of SPD and wiring caused by the installation of the SPDs is also analyzed. There is large transmission attenuation at the resonant frequency, that is in the middle of PLC transmission band from 2M to 30MHz, causes transmission rate degradation.

Key-Words: - power line communication, surge protective device, varistor, gas discharge tube, resonant frequency, inductance, wavelength, ZnO

1 Introduction

Since October 2006, PLC has been available only in-building application in Japan. Many PLC modems and related apparatus have been selling since then. In the previous paper[1], we proposed that the capacitance of varistor type SPDs affect the transmission rate of PLC modems. In order to avoid the large capacitance of varistor, we proposed to use GDT or use varistor and GDT in series. JIS (Japanese Industrial Standard) recommends installation of SPD for AC power line for new buildings and houses. SPDs can be an issue of spreading PLC modems and PLC Systems application. In this paper, we investigated how the capacitance and the inductance of varistor type SPDs that cause resonance in the PLC bandwidth and affect the PLC modem transmission rate. Firstly it is described the capacitance and inductance of SPD causes resonance at the frequency that degrades the PLC signal. Secondly, the capacitance of varistor vs. varistor-voltage and maximum current capability are analyzed from the datasheet of different varistor device manufacture. Thirdly, the inductance is analyzed that caused by SPD itself and caused by the installation of SPDs and wiring. Lastly, PLC transmission rate degradation of PLC modems that caused by SPD installation and application is analyzed.

2 Analysis of SPD characteristics

2.1 SPD resonance degrades PLC signal frequency band

Fig.1 shows the actual transmission characteristics with and without varistor type SPD mentioned in the previous paper [1]. They were measured by the PLC3000 transmission simulator of Nishiyama Corporation. Fig.2 shows the 40dB constant loss characteristics from 1M to 30MHz simulated by PLC3000 with SPD. The maximum loss is about 4MHz and this loss-frequency curve looks like the impedance of L, C and R series resonance. The capacitance and inductance of SPD seems to give maximum loss at resonant frequency not at the highest frequency. Because the measured capacitance of the SPD was 14nF, the inductance is calculated as 0.1uH from the resonant frequency. In order to simulate the transmission loss characteristics with LCR impedance, transmit and receive termination impedance is necessary. The impedance is selected 25Ω to meet the simulation result close as possible to the measured characteristics. The dotted line of Fig.1 and Fig.2 shows the simulation result above.

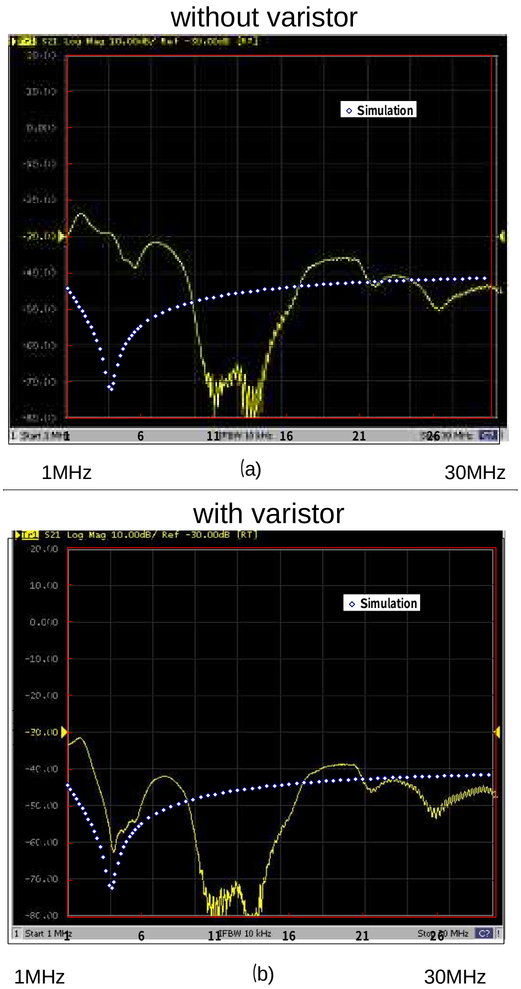


Fig.1 Transmission characteristics of actual line (a) without varistor and (b) with varistor. Dotted lines show the simulation results of the varistor

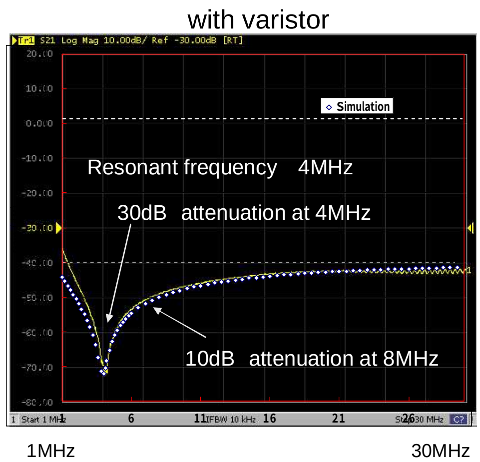


Fig.2 Transmission characteristics of 40dB flat attenuation with varistor. Dotted line shows the simulation result of the varistor

2.2 Measurement result of SPD impedance

In this paper, we measured impedance of various SPDs by measuring transmission characteristics from 1M to 100MHz. The capacitance is usually measured at 1kHz in order not to be affected by inductance and resonance. However the concern of SPD is the large attenuation at the resonant frequency, we measured all frequency including such resonant condition. The test method should be simple and applicable for high frequency test condition with minimum inductance. Fig.3 shows the test method using only 50Ω coax cables, 50Ω 20dB attenuators (ATT) and High bandwidth Network analyzer. In method A, lines between ATT and SPD terminals are connected directly at the angle of 90 degree. This is intended to have minimum electro-magnetic influence each other. In Method B, the two ATTs are connected directly and there are branches between ATTs and SPD with minimum length.

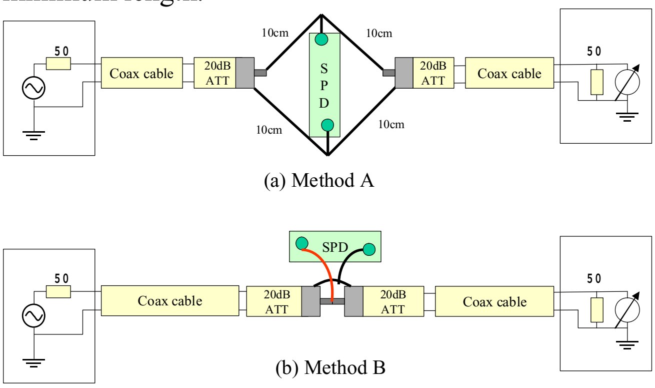
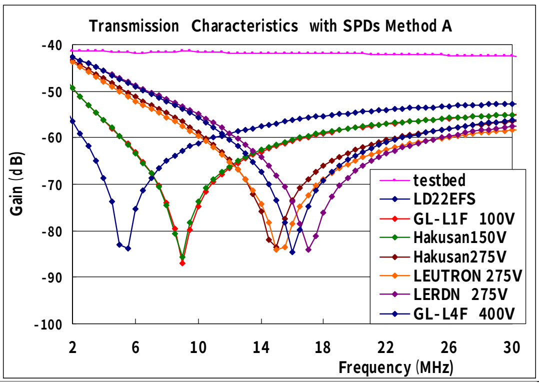


Fig.3 Transmission characteristics measurement by connecting SPD in 50 Ω coax cables and attenuators. Different wiring by (a) Method A and (b) Method B

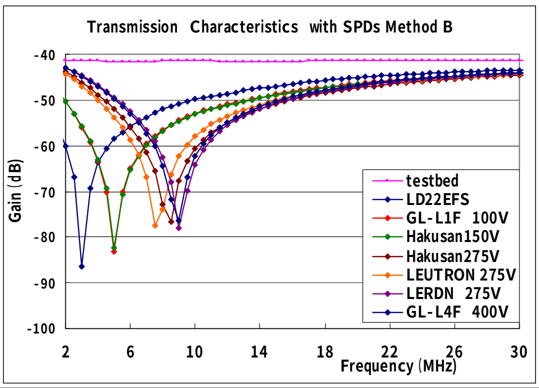
Table 1 SPDs capacitance and inductance measured and calculated by Method A(upper) and Method B(lower).

Group	Name	Spec	Length	Capacitance	Inductance	f(res)
A	LD22EFS Otowa	Uc=230VAC~ Iimp=25kA(10/350us) Up=1.3kV	7cm	12800pF 13250pF	0.07uH 0.22uH	8.9MHz 3.0MHz
B	GL-L1F Otowa	AC=110V	6cm	4720pF 4920pF	0.065uH 0.21uH	9.1MHz 5.0MHz
	Hakusan 150V	Uc=150V In=20kA, Imax=40kA Up<0.7kV	8.5cm	4690pF 4910pF	0.068uH 0.21uH	8.9MHz 5.0MHz
C	Hakusan 275V	Uc=275V In=20kA, Imax=40kA Up<1.4kV	8.5cm	1650pF 1720pF	0.07uH 0.21uH	14.8MHz 8.3MHz
	LEUTRON EPCS275	Uc=275VAC~ Iimp=20kA, Imax=40kA Imax=40kA	8.5cm	1700pF 1790pF	0.064uH 0.24uH	15.3MHz 7.7MHz
D	LERDN 385V	Uc=385V In=20kA, Imax=40kA Up<1.8kV	8cm	1370pF 1440pF	0.063uH 0.22uH	17.1MHz 8.9MHz
	GL-L4F Otowa	AC=450V	6cm	1370pF 1450pF	0.072uH 0.22uH	16.0MHz 8.9MHz

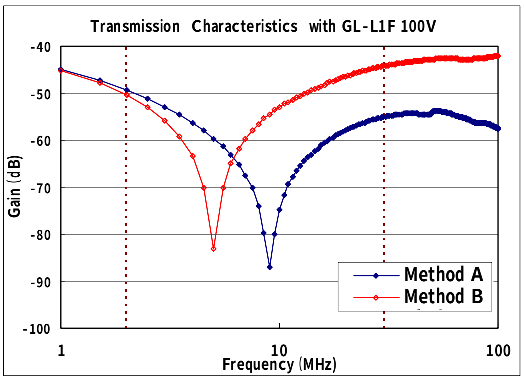
Fig4a and Fig.4b show the transmission characteristics measured by method A and method B respectively. The resonant frequency and Gain are different among SPDs. It is apparent that resonant frequencies are shifted to lower frequency by method B than Method A. Capacitance is calculated from the Gain at 1MHz, and the inductance is calculated from the resonant frequency. Table 1 shows the calculated result where upper value is by Method A and lower value is by Method B. Except Group A, there is tendency that the capacitance is smaller when the Uc voltage is larger.



(a)



(b)

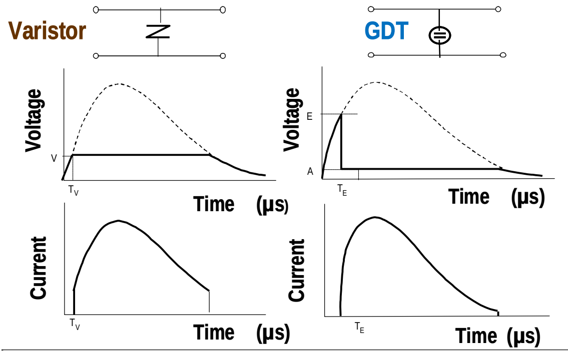


(c)

Fig.4 Transmission characteristics with various SPDs.
(a) Measured by Method A (b) Measured by Method B
(c) Difference between Method A and Method B.

2.3 Analysis of capacitance of varistor from datasheet

Varistors have used as a surge protection device that protect electrical apparatus from lighting surge voltage for a long time. Fig.5a shows the operation of varistor when surge voltage is applied. The surge voltage is cramped and the surge current flows during the cramped condition. Varistor is made of ceramic of Zinc Oxide (ZnO) powder with a little additive.



(a) (b)

Fig.5 Characteristics of varistor (a) and GDT (b) when over voltage applying.

Typical varistor has a disk shape with electrode on each side. The configuration of typical varistor looks like a ceramic capacitor, where the dielectric ceramic material of the capacitor replaced by the ZnO ceramic material. The datasheet of varistor says that the maximum surge current is proportional to the disk size. Larger disk diameter indicates larger capacitance, however higher varistor-voltage indicates smaller capacitance. The varistor-voltage is a voltage when 1 mA current flows through the varistor that means the starting point of the voltage cramp.

Fig.6a shows capacitance(Y-axis) vs. varistor- voltage (X-axis) plotted from the three device-manufactures, Panasonic, NIPPONCHEMI-CON and OHIZUMI. Those manufactures have the same diameters of disk from 5mm to 22mm respectively. The value of capacitance seems that there is inverse proportional relationship among them. It is natural that the square of the disk diameter is proportional to the capacitance. Therefore Y-axis is changed to 1/Capacitance and square of the disks are normalized to 10mmϕ shown in Fig.6b. It is found that the 10mmϕ normalized 1/Capaciance is proportional to the varistor-voltage among different device manufactures, and different production process.

Following is the analysis of the characteristics written above. Fig.7a is a physical image of varistor where almost the same size ZnO particles filled up between the electrodes.

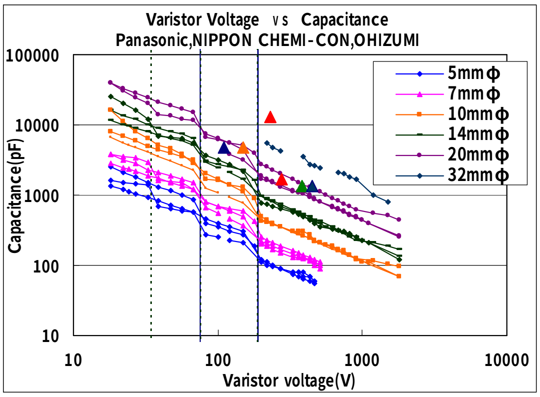


Fig.6(a) Varistor-Voltage vs. Capacitance of different manufacture disk size of 5mm to 32mm.

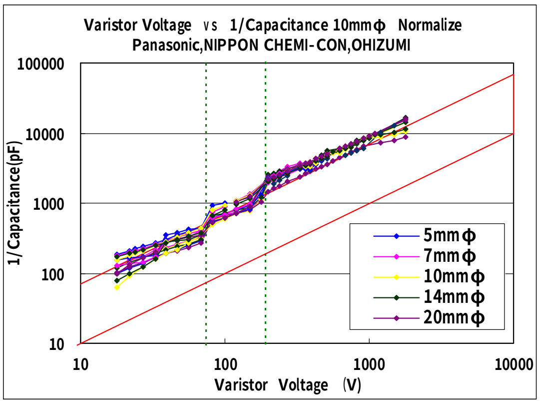
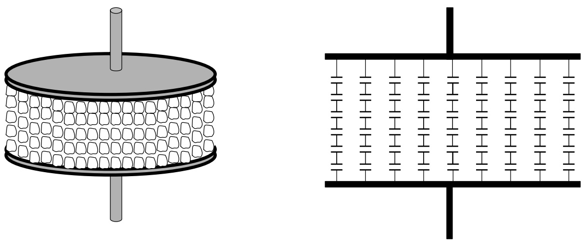


Fig.6(b) Varistor-Voltage vs. 1/Capacitor of different manufacture 10mmφ normalized.



(a) (b)

Fig.7 (a) The structure of varistor (b) The equivalent circuit of varistor consists of series and parallel capacitors between ZnO particles

The particles are low-ohmic conductor but isolated each other, so there are small capacitances around each particle. Fig.7b is a simple equivalent circuit of the varistor where many series capacitors connected between the electrodes in parallel. If the number of the series capacitor is N, the total capacitance will be 1/N. The varistor-voltage will be the sum of these capacitors' breakdown voltage. Therefore, the thickness of the disk is proportional to the number of N, and is proportional to both varistor-voltage and 1/Capacitance. The square of disk diameter is proportional to the number of parallel capacitors in line and surge current capability. It is interesting that varistor-voltage is inverse proportional to capacitance and there is not much difference among the manufactures. It is also shown in Table 1, if both current capability and varistor-voltage is the same, the capacitance is almost the same. The triangle dots shown in Fig6(a) are capacitance data of Table 1.

2.4 Analysis of inductance of varistor and wiring

Because inductance is a function of length, the inductance of 1m single wire is almost equal to 1uH. Fig.8 shows the photograph of measured SPDs. The SPD is plugged in the socket, and the socket is connected to the AC wire. The inductance exists at socket and AC wire terminals as well as SPD itself. As shown in Table 1, the calculated inductance is smaller by method A than by method B. The lengths between the SPDs terminals are 6 to 8.5cm, and the inductance values are 0.063 to 0.072uH by method A that is equal to 6.3 to 7.2cm in length. The calculated inductance seems the inductance of SPD itself. Considering the total length of socket and SPD, it is necessary to analyze the electromagnetic filed inside SPD and socket. The calculated inductance by method B is almost constant as 0.22uH that is equal to 22cm in length. There is no length such as 22cm in the test Method B, but it means the wiring around SPD can be a big issue.

Fig.8 Photograph of various SPDs

3 SPD installation and wiring issue

3.1 Power Line, MCCB and SPD position

Fig.9a and Fig.9b show typical installation of SPDs. There are two ways to install SPDs, one is to install SPD in front of MCCB (Molded Case Circuit Breaker) or behind of MCCB, recommended by IEC and JIS standard. MCCB usually has function of RCD (Residual Current Device). Fig.9a shows SPDs installed behind the MCCB, the lightning surge current flows through SPD may activate RCD then Power line may cut off. In such a case, RCD should be endured one against impulsive current. In Japan, the middle voltage 6.6kV is down to 100V by the transformer. Low-voltage is distributed by L1/L2 and N where N is neutral and connected to earth. There are SPDs between L1/ L2 and N to protective ground PE respectively. SPD has good isolation usually, but after a lot of lightning current by SPD operation, the isolation is degraded then there will be large leakage. If only one SPD loses isolation, RCD detects it then cut off the power line fault to the earth. If two SPDs lose isolation at the same time, MCCB function detects it then cut of the short circuit.

Fig.9b shows SPDs installed in front of the MCCB, the lightning surge current flows through SPD does not activate RCD. There is no SPD between N and PE. The weak point of this method is, if one of SPD loses isolation, hot voltage of L1/ L2 appear at common point A, so it is necessary to isolate point A and enclosure of the Load by GDT. It is also necessary to add a disconnector that is able to cut off the AC power current when SPD has short failure.

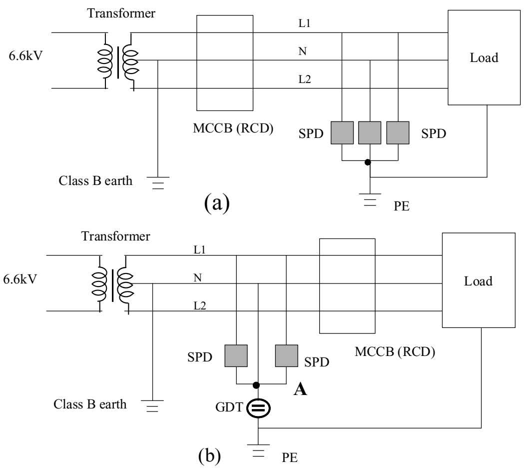


Fig.9 Two ways of SPD installation in power line.
(a) Install SPD between MCCB and electrical apparatus
(b) Install SPD between Transformer and MCCB

Following is analysis of equivalent circuit. As written above there are MCCB and/or other AC power equipment connected around SPDs by wires that have inductance. If power line and earth wire is long and the inductance larger than 1uH, it will not influenced the PLC signal. The inductance by a few cm of length may shift the resonant frequency, so smaller inductance is rather important. The two SPDs are usually in a same case or installed side by side, the inductance between them is very small. Fig.10 shows the equivalent circuit. Two SPDs, L1/L2 to PE and N to PE in Fig.9a, are connected in series. The inductance of two SPDs in series is doubled but the capacitance is halved, so the resonant frequency is same as single SPD.

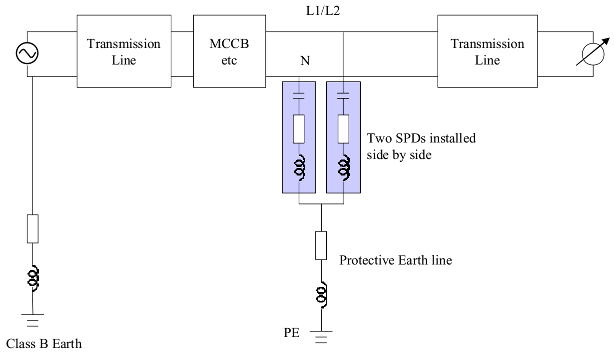


Fig.10 Equivalent circuit of SPD and wiring

3.2 GDT influence and wavelength vs. wiring

GDT means Gas Discharged Tube and is a common device for SPD as well as varistor. Inside robust ceramic case, there are two electrodes with small gap filled with special gas. When high surge voltage applied, arc discharged the current through the gap to protect electrical apparatus. The operation of GDT is shown in Fig.5b. The capacitance of GDT is only a few pF, so the degradation is only a few dB in the high PLC frequency range. Power line is designed to distribute electrical power by 50/60Hz, and is not intended to send high frequency signal such as 2M to 30MHz. If power lines are separate lines and there is free air between them, the speed of signal is same as the light speed. The wavelength of 2M to 30MHz is 10m to 150m, so the1/4 wavelength is 2.5m to 32.5m. The length of power line inside building or house is more than 2.5m, so it is necessary to consider power line as transmission line. Practically it is possible to treat circuit not as transmission lime if the length is less than 5% of wavelength. It is 25cm in case of 30MHz. Therefore SPD and its' Socket can be treated as simple electrical component of L,C and R. Between the SPD to MCCB and PE wire longer than 25cm have to be considered as transmission lines.

4 Transmission Loss and transmission rate of OFDM PLC modems

PLC modems using 2M to 30MHz now are usually use OFDM (Orthogonal Frequency Division

Multiplexing) modulation. OFDM is a multi-carrier system that uses many sub-carriers and each carrier transmits a certain transmission data. If there is noise at some frequency range, OFDM PLC modems do not use the sub-carriers of that frequency then total transmission rate or capacity is not degraded much. Because of robustness to noise, OFDM is used not only PLC but also other wireless transmission systems. Fig.11 shows image of Signal to Noise (S/N) relation of multi-carrier system. The output transmit level of the modem is large and constant but the receive level is attenuated due to the characteristics of AC power line shown by the dotted line. There is additional attenuation by the resonance of SPDs as described. The noise level is a sum of the quantization noise of the modem and the noise at AC power line. Therefore the S/N ratio of each sub-carrier is different and written as S/Nn where n is the number of sub-carrier.

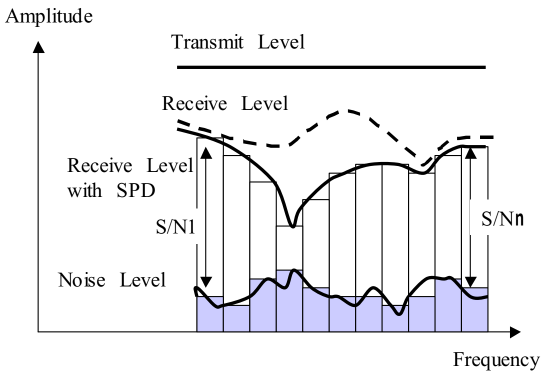


Fig.11 The image of Signal to Noise ratio and transmission characteristics with SPDs in a multi-carrier system.

Most of PLC modems today show good transmission performance if the signal attenuation is less than 50dB that means S/N of each sub carrier is large enough. If there is SPD that gives additional loss at resonant frequency as shown in Fig.11, it is possible to estimate the influence of SPD by the sum of S/Nn degradation.

5 Conclusion

The issue of SPD influence on Power Line Communication is described in the previous paper. In this paper, we analyzed that the influence of varistor type SPD is caused by the capacitance and inductance of SPD that causes resonance at the middle of PLC bandwidth. The capacitance of varistor is proportional to the maximum surge current that is the square of diameter of varistor disk, and is inverse proportional to the varistor-voltage. There is not much difference among varistor device manufactures.

The inductance of SPD is measured as 0.063uH to 0.072uH caused by the physical length of SPD that is about 6cm to 8.5cm. The capacitance and inductance of SPD caused 30dB attenuation or more at resonant frequency. It is important that the capacitance of SPD does not changed but the inductance by wire will shift the resonant frequency. PLC transmission rate in actual power line will be changed according to the installation and wiring of the SPDs. Large inductance will not influence the PLC bandwidth but it means long wire length close to 1/4 wavelength or more, then reflection issue will be arisen. Two SPDs connected to L1/L2 to PE and N to PE gives smallest inductance because they are in a same case or installed side by side. They are connected in series and connected across the PLC signal source. The relation between attenuation and transmit rate can be estimated because the total transmission rate is the sum of each multi-carrier transmission rate. The capacitance of GDT type SPD is so small that only a few dB of degradation is caused by the mismatching.

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