1~ 30MHz 광대역 전력선 통신을 위한 고압 배전선의 임피던스 특성 측정 및 해석

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Impedance measurement and analysis of overhead medium voltage power lines for broad band power line communication (BPLC

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Abstract – In this paper, impedance characteristics of overhead medium-voltage (MV) power lines is reported for power line communication (PLC) over an MV power line network. For analysis, a two-port equivalent network model of MV power lines is derived. By applying the transmission line theory, reflection behavior and impedance of power lines are investigated. For verification, impedance of power lines is measured at a test field for an MV PLC. The results show that impedance of MV power lines is between 200Ω and 300Ω and converges to a half of their characteristic impedance.

1. Introduction

Recently, power line communication (PLC) over medium-voltage (MV, 22.9 kV) power lines is investigated very hard for low cost Internet service and Voice over IP service (VoIP). For high data rate telecommunication service over an MV power lines, it is necessary that channel characteristics of MV power lines such as noise, impedance, and attenuation should be studied [1-3]. Analysis of impedance particularly plays an important role on impedance matching closely related to better transmission behavior and measurement of noise in channel.

In the paper, impedance characteristics of overhead MV power lines is described for broadband PLC in a frequency range between 1 MHz and 30 MHz. Until now, few papers have been published, compared to several good papers regarding channel characteristics of low-voltage power lines [4-5]. One of the reasons is that it is difficult to measure the impedance of MV power lines in still working on power line distributions and their tough surroundings. For the analysis of impedance characteristics, characteristic impedance and complex propagation constant are derived using data of overhead MV power lines. Also, a two-port equivalent model of an MV power line network is presented and with an aid of the model, reflection and impedance of MV power lines are calculated. For verification of calculation, both input impedance and impedance of MV power lines are measured at an MV PLC test field.

In the next sections, an MV PLC test field for Internet service over MV power lines is introduced. The procedure of deriving an equivalent model and then calculating impedance is provided in detail. Finally, impedance of MV power lines is measured in the test field for verifying the calculation.

2. Overhead MV power lines and a two-port equivalent model

2.1 Overhead MV power lines

In Fig. 1(a), a configuration for PLC over an MV power line network in an MV PLC test field is schematically displayed. An MV PLC network contains three main parts of MV power lines, coupling units, and a coaxial lines with a PLC modem. The coupling unit is composed of a coupling capacitor (C) of 2 nF for communication signals, an inductor (L) of 1 mH for preventing low frequency high power at signal ports, and a cut-off-switch (COS) for protecting the coupling capacitor and inductor from dangerous overload of tough MV power lines. The coaxial line has characteristic impedance of 75Ω.

As an overhead MV power line cable in the test field of PLC on MV power lines, an ACSR-OC (Aluminum Conductor Steel Reinforced Outdoor Cross-linked Polyethylene insulated Wires) cable is used. The cable consists of mainly three concentric layers of six aluminum cores, a steel core of 3.5 mm diameter in the middle of the six aluminum cores to reinforce the aluminum cores, and a dielectric insulator of cross-linked (XL) polyethylene. The diameter of two metal layers is 9.7 mm together, and thickness of insulator is 3 mm. Here, for analysis of power line cables, it is assumed that two metal layers of the MV cable can be thought of as a single conductor core of 9.7 mm diameter coated by an XL polyethylene. The reason is that a skin depth is small and wavelength is much longer than the power line's radius in the frequency between 1 MHz and 30 MHz. For signal input, a coupling arrangement of wire-to-ground (WTG) using a power line out of three power lines and a neutral line is adopted in the test field. It is true that a power line network can be considered as a two-wire transmission line network, using the image theory. Therefore, for the WTG case, a characteristic impedance of MV power lines, can be obtained from

$$Z_{0p} = \frac{\eta}{2\pi\sqrt{\varepsilon_{r,eff}}} \ln(\frac{2D}{a}) \tag{1}$$

where $D(>>a)$ is height of power lines above the ground, a is metal radius of power line, and a wave impedance, η=377Ω [6]. In calculating Z_{0p}, resistance per unit length, R and conductance per unit length, G are not included because the amounts are much smaller

than reactance. Also, in order to consider the effect of the dielectric insulator, an equivalent effective dielectric constant in a medium between two wires, $\epsilon_{r,eff}$ is numerically calculated using conformal mapping method [7]. It should be pointed out that the imperfect ground effect in [8] is neglected due to little influence on characteristic impedance and propagation constant.

In the test field, the height D of 13 m and the radius a of 4.85 mm are measured. The effective dielectric constant, $\epsilon_{r,eff}$ of 1.033 is calculated. Thus, from (1), characteristic impedance of MV power lines, Z_{0p} of 50 Ω is obtained.
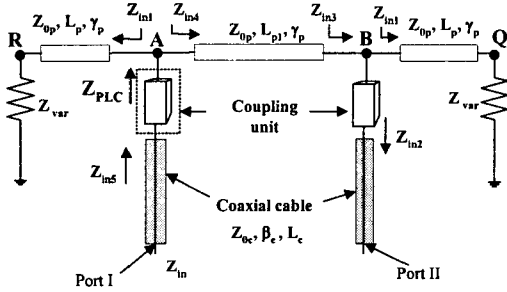

Fig 1. (a) A schematic configuration of an MV PLC test field. (b) Two-port equivalent model of a MV power line network.

2.2 Two–port equivalent network model and impedance calculation

In Fig. 1(b), a two-port equivalent model of an MV power line network is presented. As is shown, an MV power line is modeled by characteristic impedance Z_{0p}, complex propagation constant γ_p, and lengths of power lines, L_p and L_{pl}. By considering an attenuation constant of power lines, a complex propagation constant, γ_p is given as [6],

$$\gamma_p = \alpha_p + j\beta_p$$

with

$$\alpha_p \approx \frac{1}{2}\left(\frac{R}{Z_{0p}} + GZ_{0p}\right), \quad \beta_p \approx \omega\sqrt{LC}$$

$$R = \frac{1}{2\pi a}\sqrt{\frac{\pi f \mu_0}{\sigma}}, \quad G = \left(\frac{2\pi\alpha\varepsilon_{r,eff}\varepsilon_0\tan\delta}{\ln(D/a)}\right), \quad L = \frac{\mu_0}{2\pi}\ln(D/a), \quad C = \frac{2\pi\varepsilon_{r,eff}\varepsilon_0}{\ln(D/a)}.$$

ε_0 and μ_0 are permittivity and permeability of free space, respectively.

Also, a load impedance of Z_{var} is supplemented as a reflection-free termination to consider the effect of the MV power lines that exists in both left of point R and right of point Q. Since lengths of MV power line, L_p and L_{pl} are generally much longer than wavelength in the frequency, MV power lines can be assumed as a long wire traveling antenna, and then Z_{var} is given as Z_{0p} [9].

Finally, a coaxial line for connecting a coupling unit and a PLC modem is modeled by characteristic impedance Z_{0c}, propagation constant β_c, and length L_c of 12.7 m.

Using the two-port equivalent network, impedance of MV power lines Z_{PLC} is calculated as

$$Z_{PLC} = Z_{in1} \parallel Z_{in4} = \frac{Z_{in1} \cdot Z_{in4}}{Z_{in1} + Z_{in4}} \tag{2}$$

where

$$Z_{in1} = Z_{0p}\frac{Z_{var} + jZ_{0p}\tanh(\gamma_p L_p)}{Z_{0p} + jZ_{var}\tanh(\gamma_p L_p)},$$

$$Z_{in2} = Z_{0c}\frac{50 + jZ_{0c}\tan(\beta_c L_c)}{Z_{0c} + j50\tan(\beta_c L_c)},$$

$$Z_{in3} = Z_{in1}\parallel\left(\frac{Z_{in2}(1 - \omega^2 LC) + j\omega L}{-\omega^2 LC + jZ_{in2}\omega C}\right),$$

$$Z_{in4} = Z_{0p}\frac{Z_{in3} + jZ_{0p}\tanh(\gamma_p L_{p1})}{Z_{0p} + jZ_{in3}\tanh(\gamma_p L_{p1})}$$

with

$$Z_{0p} = Z_{var} = 507\Omega, \; Z_{0c} = 75\Omega, \; \beta_c = \omega/(c_0 \cdot \sqrt{1.5}),$$

$$L_{p1} = 600 \text{ m}, L_{p1} = 800 \text{ m}.$$

C_0 is light velocity of free space.

Also, the input impedance Z_{in} is obtained as

$$Z_{in} = Z_{0c}\frac{Z_{in5} + jZ_{0c}\tan(\beta_c L_c)}{Z_{0c} + jZ_{in5}\tan(\beta_c L_c)} \tag{3}$$

with

$$Z_{in5} = \frac{-j\omega L(j\omega C \cdot Z_{PLC} + 1)}{1 - \omega^2 LC + j\omega C \cdot Z_{PLC}}.$$

2.3 Impedance measurement in the test field

Using a vector network analyzer (HP8753D), impedance of MV power lines is measured at three different test points in the test field. The procedure is that first, scattering parameter is measured and then input impedance is calculated as

$$Z_{in, mea} = 50\frac{1 + S_{11}}{1 - S_{11}}. \tag{4}$$

Second, with the data of the coupling unit and the coaxial cable previously given, impedance of an MV power line network is derived as

$$Z_{PLC,mea} = \frac{j\omega L(1 - j\omega C \cdot Z_{in5,mea})}{\omega^2 LC - 1 + j\omega C \cdot Z_{in5,mea}} \tag{5}$$

with

$$Z_{in5, mea} = Z_{0c}\frac{Z_{in, mea} - jZ_{0c}\tan(\beta_c L_c)}{Z_{0c} - jZ_{in, mea}\tan(\beta_c L_c)}.$$

Fig. 2 shows the calculated result of input impedance at a port I, Z_{in} and three measurements of input impedance at three different points. As is shown, the calculation is in a good agreement with the measurement. It can be seen that input impedance is not constant. It is due to impedance mismatch between the coaxial cable and power lines. Thus, it should be noted that broadband impedance matching is necessary at the point between the coaxial cable and the coupling unit, not an input terminal connected to a PLC modem.
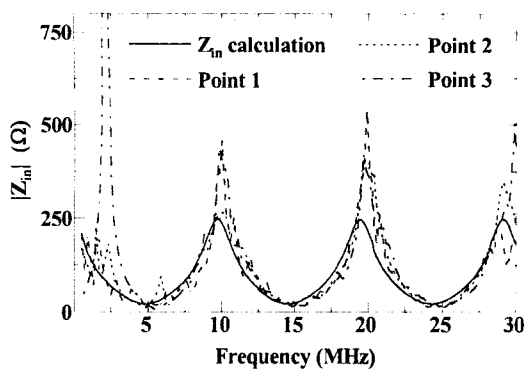
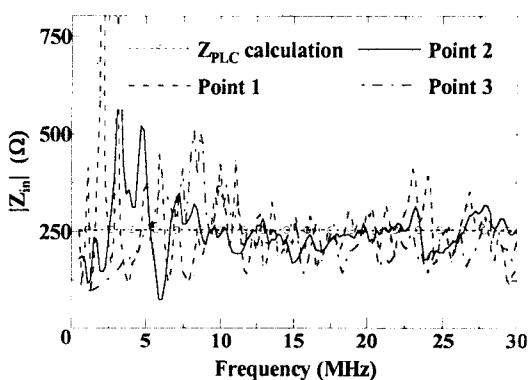Fig. 2. Calculation and three measurements of input impedance

Fig. 3. Calculation and three measurements of MV power line i
mpedance.

In Fig. 3, measurement and calculation of impedance for MV power lines only are shown. The calculation has a nearly constant value of about 250Ω. It can be explained by considering MV power lines as a long wire traveling antenna. It can be said that the load impedance Z_{tar} is added to two long wire antennas as a reflection-free termination, and then input impedance is given as a half of Z_{tar}[9]. Therefore, the calculation comes to nearly a half of Z_{0p}, 253.5Ω. Measurement shows that the impedance is between 200Ω and 300Ω, and the averaging impedance is likely to converge to a half of Z_{0p} like the calculation. Also, an MV power line network has few resonant frequencies, comparing to a low-voltage power line network [4]. One of the most important results is that broadband matching is possible and impedance should be matched with about or more than 250Ω at the terminal of the coupling unit in this case in order to achieve broadband impedance matching of MV power lines. Impedance fluctuation in lower frequency is due to the fact that impedance of the coupling capacitor becomes larger and in measurement, additionally channel noise is severer in lower frequency.

3. Conclusion

This paper reports the impedance characteristics of a medium voltage power lines for broadband power line communication (BPLC). The analytic calculation

method of power line impedance is presented. Measurement is performed at three different points and the calculation has a good agreement with the measurement results. Power line impedance comes to a half of characteristic impedance Z_{0p}, 253.5Ω with increasing frequency. Results will be well used for the impedance matching and noise analysis of MV power line.

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