In-door Power-line Impedance Measurement up to High Frequency (10KHz – 70MHz)

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Abstract

In this paper, we propose an implementation of I-V method to determine the impedance on power distribution circuits at a frequency range from 10KHz to 70MHz using a network analyzer and a circuit composed by a balun (balanced-to-unbalanced), a transformer and a high-pass-filter. To evaluate the reliability the obtained results were compared with those measured by an impedance analyzer. The efficacy of the proposed method is shown by measuring the power-line impedance in our laboratory to obtain the statistical properties of impedance. The statistical properties of electrical unbalance on the power-line are also measured by means of the impedance difference between Line-Earth and Neutral-Earth.

Keywords: Measurements and Channel Characterization, In-door Communications, Power-line Impedance Measurements, Distributed Circuit Modeling, Impedance Measurement, I-V method.

1. Introduction

Power-line, considered as a communication channel, has signal attenuation and reflections caused by its impedance properties. The power-line network can be modeled by means of a distributed constant circuit theory at the high frequency band[1]. From this point of view, the power-line impedance is an important parameter, because, once using it, we can estimate the transfer function between a transmitter and a receiver. We can also analyze the effect of impedance matching at the end of the power-line branches[2].

In this paper, an impedance measurement method is proposed, that consists in monitoring the current and voltage (I-V method[3]) of a measurement circuit, to which power-line is connected as a load. The objective is to determine the impedance of power distribution circuits in a frequency range from 10KHz to 70MHz, where the measurement of the range from 30M to 70MHz is an effort to characterize the power-line channel for a future modem design. Note that the current PLC modems utilize the frequency range under 30MHz, so that the most works of channel characterization have been done for the frequency range under 30MHz. The measurement circuit is composed of a network analyzer, a balun and a high-pass-filter.

The measured results were compared to those of an impedance analyzer to estimate the reliability of the proposed method. This comparison is made by using resistors that simulate the variations of power-line impedance.

Finally, the impedance in the authors’ laboratory of Ehime University was measured to check the efficacy of the proposing method, as well as to describe the statistical properties of impedance in this situation.

2. Measurement Method

2.1. Principle

The technique of impedance measurement, utilized in this paper, can be illustrated with a block diagram shown in Figure 1. The parameters measured were $V_1$ and $I_1$, since it is difficult practically to monitor $V_2$ and $I_2$ because they are a part of active power-line.
Monitoring $V_1$ and $I_1$ the impedance $Z$ will be measured, but it includes the impedance of an interface circuit. Our aim is the power-line impedance of $Z_{pl}$, in order to obtain it we considered the interface circuit as a black box, and determined its four-terminal constants, $A, B, C$, and $D$, of the transmission matrix as follows.

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} \triangleq \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

(1)

That is

$$V_1 = AV_2 + BI_2$$

(2)

$$I_1 = CV_2 + DI_2$$

(3)

$$Z \triangleq \frac{V_1}{I_1} = \frac{AV_2 + BI_2}{CV_2 + DI_2}$$

(4)

where

$$A = \left[ \frac{V_1}{V_2} \right]_{I_2 = 0}$$

(5)

$$B = \left[ \frac{V_1}{I_2} \right]_{V_2 = 0}$$

(6)

$$C = \left[ \frac{I_1}{V_2} \right]_{I_2 = 0}$$

(7)

$$D = \left[ \frac{I_1}{I_2} \right]_{V_2 = 0}$$

(8)

Then

$$\begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \frac{1}{AD - BC} \begin{bmatrix} D & -B \\ -C & A \end{bmatrix} \begin{bmatrix} V_1 \\ I_1 \end{bmatrix}$$

(9)

$$V_2 = \frac{DV_1 - BI_1}{AD - BC}$$

(10)

$$I_2 = -\frac{CV_1 + AI_1}{AD - BC}.$$ 

(11)

Therefore

$$Z_{pl} \triangleq \frac{V_2}{I_2} = \frac{DV_1 - BI_1}{-CV_1 + AI_1} = \frac{DZ - B}{-CZ + A}.$$ 

(12)

After characterization of the four-terminal constants $A, B, C$ and $D$ of the interface circuit and measurement of the total impedance $Z$ of the interface circuit plus power-line, the power-line impedance $Z_{pl}$ can be obtained.

### 2.2. Practical Approach

The practical circuit is shown in Figure 2. Comparing the practical circuit with the block diagram of Fig.1, the signal source consists of a network analyzer (ADVANTEST Co., R3754B), a balun and a transformer. The capacitors used for a high-pass-filter, resistors, and an AC plug are the interface circuit. The balun was inserted to avoid disturbances from the unbalanced signal source (network analyzer) to a balanced circuit (power-line). The transformer and the high-pass-filter were used to protect the circuit from the line voltage of 100V, as well as to minimize the noise in low frequency band of less than 10KHz.

By using two input-ports of network analyzer we could measure $V_1/V_{gh}$. The total impedance $Z$ could obtain as

$$Z = \frac{V_1}{I_1} = \frac{V_1}{V_{gh}/22}.$$ 

(13)

To obtain $Z_{pl}$, we had to measure $Z$ when the terminals “i” and “j” were opened, shorted, connected to a known load ($Z_l = 51.1\Omega$), and connected to power-line[3]. The corresponding “Z”s are denoted by $Z_{op}$, $Z_{sc}$, $Z_{xl}$, and $Z_{xm}$, respectively. When the terminals are opened, $I_2 = 0$. From eq.(4), $Z_{op}$ is given as

$$Z_{op} = \frac{AV_2 + BI_2}{CV_2 + DI_2} = \frac{A}{C}.$$ 

(14)

For the shorted circuit, $V_2 = 0$.

$$Z_{sc} = \frac{B}{D}.$$ 

(15)

When they were connected to the known load,

$$Z_{xl} = \frac{A\frac{V_2}{I_2} + B}{C\frac{V_2}{I_2} + D} = \frac{AZ_l + B}{CZ_l + D}.$$ 

(16)

When connected to power-line,

$$Z_{xm} = \frac{AZ_{pl} + B}{CZ_{pl} + D}.$$ 

(17)
From eqs. (14), (15), (16), and (17)

\[ A = Z_{op} C, \]  \hspace{1cm} (18)

\[ B = Z_{sc} D, \]  \hspace{1cm} (19)

\[ Z_{xl} = \frac{AZ_l + DZ_{sc}}{CZ_l + D}, \]  \hspace{1cm} (20)

and

\[ Z_{pl} = \frac{B - DZ_{zm}}{CZ_{zm} - A}. \]  \hspace{1cm} (21)

From eqs. (18) and (19), eqs. (20) and (21) can be given as

\[ \frac{D}{C} = \frac{(Z_{op})(Z_l) - (Z_{xl})(Z_l)}{Z_{xl} - Z_{sc}}, \]  \hspace{1cm} (22)

and

\[ Z_{pl} = \frac{D}{C} \frac{(Z_{sc} - Z_{zm})}{(Z_{zm} - Z_{op})}, \]  \hspace{1cm} (23)

respectively. Finally from eq. (22), eq. (23) is given as

\[ Z_{pl} = \frac{(Z_l)(Z_{op} - Z_{xl})(Z_{sc} - Z_{zm})}{(Z_{xl} - Z_{sc})(Z_{zm} - Z_{op})}, \]  \hspace{1cm} (24)

where the parameters \( Z_{op}, Z_{xl}, Z_{sc}, \) and \( Z_{zm} \) had been measured by eq. (13).

### 3. Reliability of Measurement

Reliability of the proposing method was examined by comparing the obtained results of the proposed method with those of an impedance analyzer (HP 4291B with Low-impedance-test-head and 16092A option). Resistors were connected at the terminals “i” and “j” of Fig. 2, and their impedance was measured instead of power-line. Figure 3 shows the measurement error of the proposing method, where the measured values by the impedance analyzer were assumed correct. Although the measurement error of the impedance analyzer is less than 5% in the figures’ range, that of the proposed method is almost less than 20% except the area of less than 10Ω and more than 10MHz. The most reliable impedance of the proposed method is around 100Ω all over the frequency range. The obtained reliability is enough for the purpose of measuring the power-line impedance described in Sec. 4.

### 4. Impedance of Power-line

The impedance of 25 outlets of our laboratory was measured. Twelve outlets in 25 had an earth terminal, that is three wires were connected to the twelve outlets. Figure 4 shows the result of 25 outlets. The measured values are plotted by means of a probability distribution function.
The impedance is an increasing function less than 10MHz, although it changes to fluctuate around 90Ω due to the property of the distributed constant circuit theory[1]. This tendency is the same as our previous results which were measured for the range under 30MHz[1], except the center impedance value for the fluctuation was 40Ω. Note that the previous measurement of [1] was based on the network analysis method that utilizes the reflection coefficient[3].

Figure 5 shows the impedance properties of the 12 outlets with an earth terminal, which were selected from the 25 outlets. Figure 5(a) shows impedance between terminals of Line and Neutral, that is “normal-mode” or “differential-mode” impedance. The trend is the same as Figure 4, that is an increasing and fluctuating function, except the center impedance value for the fluctuation is changed to become a smaller value of 40Ω.

The impedance between “Line and Earth”, or “Neutral and Earth” is plotted together in Fig.5(b). Comparing Fig.(a) with (b), the impedance of Fig.(b) is higher than that of Fig.(a) generally. When no appliance is connected to an outlet, the impedance is high, i.e., about 100Ω, especially at low frequency (less than 1MHz) as shown in Fig.(b). When appliances are connected, the so-called Y-capacitor (line bypass capacitor)¹ affects the result when the frequency is less than 1MHz.

Figure 5(c) shows absolute values of the difference between Line-Earth ($Z_{\text{Line-Earth}}$) and Neutral-Earth ($Z_{\text{Neutral-Earth}}$). This is an indication of electrical unbalance, which converts a portion of differential-mode signals to unwanted common-mode signals. The common-mode current produces a radiated electromagnetic field, which interferes with the reception of radio communication services[4]. The difference, i.e., the electrical unbalance, increases when the frequency is more than 300KHz.

5. Conclusion

¹e.g., http://www.murata.com/emc/knowhow/pdfs/te04ea-1/30e.pdf
In this paper, an impedance measurement method based on the I-V method was proposed. The available frequency range was from 10KHz to 70MHz, and the impedance range was from 1 to 1KΩ. The measurement error of the proposed method was almost less than 20% except the area of less than 10Ω and more than 10MHz. Using the proposed method, the impedance of power-line was measured, and its statistical properties were described. The trend of the obtained properties was the same as our previous results which were measured at the range under 30MHz. Moreover, the tendency was also the same even if the frequency range was expanded up to 70MHz. The electrical unbalance was finally measured by means of the impedance difference between Line-Earth and Neutral-Earth. The difference was an increasing function when the frequency was more than 300KHz.

Instead of using an expansive impedance analyzer, the power-line impedance can be measured by the proposed method with a reasonable reliability if a network analyzer can be equipped. The proposed measurement circuit is almost the same as that for practical PLC modems. Therefore, if the proposed method is implemented in the modems, an adaptive channel-estimation will become possible. That will be our future work.

Acknowledgments

The first author would like to thank the professors at Ehime University and the Japanese government that provided the opportunity to participate in a technical and cultural exchange. During this program, the research in this paper was developed.

References


