PAPER Special Issue on Measurements and Control of Electromagnetic Interference

Method for Estimating Electromagnetic Interference due to Unbalance in Telecommunications Line

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SUMMARY Information technology equipment connected to telecommunications line can be a source of electromagnetic interference. Two sources of interference have been under evaluation. One is the digital pulses in the switching regulator and the clock oscillator, and the other is the signal's common mode voltage. In this paper, the interference-inducing mechanism for the signal's common mode voltage and a method for measuring the interference are described. An equivalent circuit representing both the equipment and the line is derived on the basis of the interference-inducing model. A method for estimating the signal's common mode voltage from the differential mode voltage and the line unbalance is obtained using the equivalent circuit. It is confirmed that the level difference between the estimated and the measured common mode level is less than 3 dB.

key words: *interference, EMC, EMI, common mode, unbalance, telecommunications line*

1. Introduction

Wide introduction of digital, high-speed and broad-band equipment in the field of advanced information systems has resulted in a serious increase in electromagnetic noise and the resulting interference among systems. As for telecommunications systems, this interference has also initiated a global interest in the problems of electromagnetic compatibility (EMC). To restrict electromagnetic noise and to achieve EMC, the International Special Committee on Radio Interference (CISPR) has been investigating the additional requirements for emission from information technology equipment connected to public networks or local area networks[1].

Two sources of interference have been under evaluation. One is the digital pulses of the switching regulator and clock oscillator. The harmonics of the digital pulses, which can be unintentionally coupled via power mains cable, telecommunications cable or by direct radiation, can be a significant source of interference. The other is the signal's common mode voltage. The common mode voltage is the mean voltage appearing between the telecommunications line and the ground. The signal's common mode voltage is generated by both equipment unbalance and telecommunications line unbalance. An interference current due to the voltage flows through the circuit between the telecommunications line and the ground. The current can constitute a potential source of interference[2]–[5]. The interference caused by the switching regulator and the clock oscillator can be measured by an Impedance Stabilization Network (ISN) for telecommunications signal ports[6]. However the interference-inducing mechanism and the method for measuring the signal's common mode voltage have not yet been clarified. This voltage is important from the interference viewpoint in cases such as Integrated Services Digital Network (ISDN) telecommunications signals, where the signal frequency range overlaps the radio receiver range[2],[7].

In this paper, a method for estimating the interference due to unbalance in telecommunications line is described. First, we show by experiment that the unbalance of the telecommunications line causes interference to radio receivers. Then, an interference-inducing model for the signal's common mode voltage is discussed, and the relationship between the voltage and line unbalance is analyzed. Finally, a method for measuring the signal's common mode voltage is proposed on the basis of the analysis. Measurement results obtained by using the proposed method are also described. As a result, a method for estimating the common mode voltages at telecommunications signal ports, including the signal's common mode voltage, is obtained.

2. Experiment for Evaluating Interference due to Line Unbalance

An experiment was carried out to evaluate the interference caused by telecommunications line unbalance. The layout of the experiment is shown in Fig. 1. A differential signal is supplied at one end of an overhead cable, and the radiated magnetic field is measured by a loop antenna set under the cable. The antenna is about 4 m from the overhead cable and about 15 m from the signal supply point.

The measured magnetic field strength, H_L, is converted into electric field strength, E_L, by Eq. (1) to evaluate the approximate electric field strength radiated from the cable.

Manuscript received August 16, 1991.
Manuscript revised October 9, 1991.

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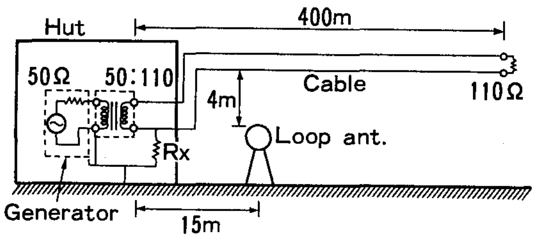

Fig. 1 Experimental layout for measuring field strength radiated from telecommunications line.

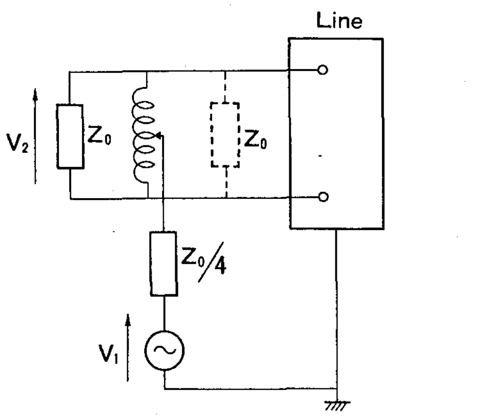

Fig. 2 *LCL* measurement circuit recommended by CCITT.

$$E_L(\mathrm{dB}) = H_L(\mathrm{dB}) + 20\log(377) \quad (1)$$

Here, 377(ohms) is the intrinsic impedance of free space. In Fig. 1, the transformer, whose unbalance is small, simulates the signal transmission output of the equipment. The line unbalance is controlled by the resistance R_X. The line unbalance and equipment unbalance are usually represented by longitudinal conversion loss (*LCL*). Where *LCL* stands for unbalance about earth as defined by CCITT[8]. Figure 2 shows the *LCL* measurement circuit recommended by CCITT. A transformer is connected to a balanced pair cable, which is terminated by the characteristic impedance Z_0. A signal is supplied to the center tap of the transformer through the $Z_0/4$ impedance. The *LCL* is defined by

$$LCL = 20\log(V_1/V_2) \quad (2)$$

where V_1 is the signal oscillator level and V_2 is the level appearing between the balanced pair.

The relation between *LCL* of the line and the radiated electric field strength is measured for 200 kHz, 1 MHz and 3 MHz, where the primary components of the digital telecommunications signal for a balanced pair are located. The measurements are plotted in Fig. 3, showing that the radiated electric field strength decreases in proportion to the *LCL* of the line at all three frequencies. This result means that line unbalance may cause electromagnetic interference to radio receivers.

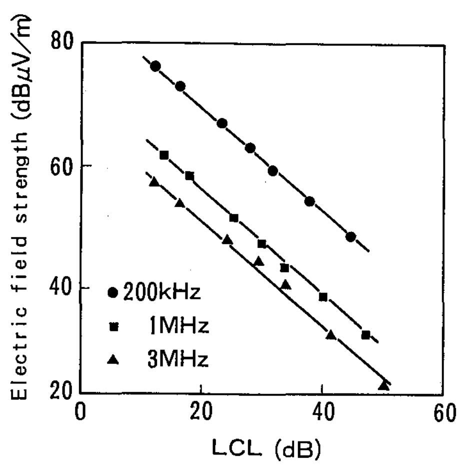

Fig. 3 Relation between the *LCL* of the line and the radiated electric field.

3. Method for Estimating the Signal's Common Mode Voltage

In this section, we propose a method for estimating the signal's common mode voltage from the signal's differential mode voltage and the line unbalance.

3.1 Theoretical Analysis of Signal's Common Mode Voltage

The interference caused by line unbalance is studied on the basis of an interference-inducing model. The mechanism which induces the radiated electric field is summarised in Fig. 4. A common mode voltage, V_L, appears between the telecommunications signal ports of the equipment and the ground, and an interference current, I_L, flows through the circuit between the telecommunications line and the ground. An electric field strength, E_L, is induced by current I_L. In this paper, the common mode voltage, V_L, is employed to study the interference-inducing mechanism since measuring V_L is easier and reproducible than measuring I_L or E_L[4],[5].

The equivalent circuit of the network consisting of the telecommunications equipment and the line shown in Fig. 5 can be derived. In this figure, I_s is the current source of the telecommunications signal, I_c is the current source of the common mode interference caused by a switching regulator and a clock oscillator, Z_1+Z_2 and Z_3+Z_4 represent the differential mode input impedances of the telecommunications line and signal ports of the equipment. Z_L and Z_C represent the common mode input impedances of the telecommunications line and signal ports of the equipment. V_A and V_B are the voltages appearing between each wire and the ground. In the equivalent circuit shown in Fig. 5, the differential mode voltage, V_S, and the common

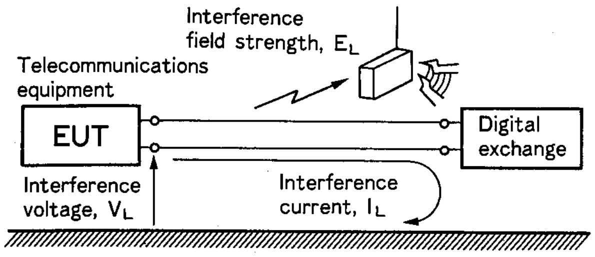

Fig. 4 Interference inducing mechanism via telecommunications signal ports of equipment under test (EUT).

mode voltage, V_L, are defined as

$$V_S = V_A - V_B \quad (3)$$

$$V_L = (V_A + V_B)/2 \quad (4)$$

V_A and V_B are obtained by solving the following node equations.

$$(V_A - V_C)/Z_1 + (V_A - V_D)/Z_3 = I_C + I_S \quad (5)$$

$$(V_B - V_C)/Z_2 + (V_B - V_D)/Z_4 = I_C - I_S \quad (6)$$

$$(V_A - V_C)/Z_1 + (V_B - V_C)/Z_2 = V_C/Z_C \quad (7)$$

$$(V_A - V_D)/Z_3 + (V_B - V_D)/Z_4 = V_D/Z_L \quad (8)$$

where

$$V_C = (V_A/Z_3 + V_B/Z_4)/(1/Z_3 + 1/Z_4 + 1/Z_C) \quad (9)$$

$$V_D = (V_A/Z_1 + V_B/Z_2)/(1/Z_1 + 1/Z_2 + 1/Z_L) \quad (10)$$

V_S and V_L are given by

$$V_S = \frac{1}{2(A*B - C^2)}\left\{I_C \frac{Z_1 - Z_2}{(Z_1 + Z_2) Z_L + Z_1 Z_2} + I_C \frac{Z_3 - Z_4}{(Z_3 + Z_4) Z_C + Z_3 Z_4} + I_S \frac{Z_1 + Z_2}{(Z_1 + Z_2) Z_L + Z_1 Z_2} + I_S \frac{Z_3 + Z_4}{(Z_3 + Z_4) Z_C + Z_3 Z_4}\right\} \quad (11)$$

$$V_L = \frac{1}{2(A*B - C^2)}\left\{I_C \frac{Z_1 + Z_2 + 4Z_L}{(Z_1 + Z_2) Z_L + Z_1 Z_2} + I_C \frac{Z_3 + Z_4 + 4Z_C}{(Z_3 + Z_4) Z_C + Z_3 Z_4} + I_S \frac{Z_1 - Z_2}{(Z_1 + Z_2) Z_L + Z_1 Z_2} + I_S \frac{Z_3 - Z_4}{(Z_3 + Z_4) Z_C + Z_3 Z_4}\right\} \quad (12)$$

where

$$A = (Z_2 + Z_L)/(Z_0 * Z_L + Z_1 * Z_2) + (Z_4 + Z_C)/(Z_0 * Z_C + Z_3 * Z_4) \quad (13)$$

$$B = (Z_1 + Z_L)/(Z_0 * Z_L + Z_1 * Z_2) + (Z_3 + Z_C)/(Z_0 * Z_C + Z_3 * Z_4) \quad (14)$$

$$C = -Z_L/(Z_0 * Z_L + Z_1 * Z_2) - Z_C/(Z_0 * Z_C + Z_3 * Z_4) \quad (15)$$

$$Z_0 = Z_1 + Z_2 = Z_3 + Z_4 \quad (16)$$

Rewrite V_L as

$$V_L = V_{LC} + V_{LSE} + V_{LSL} \quad (17)$$

where

$$V_{LC} = \frac{I_C}{2(A*B - C^2)}\left\{\frac{Z_0 + 4Z_C}{Z_0 Z_C + Z_1 Z_2} + \frac{Z_0 + 4Z_L}{Z_0 Z_L + Z_3 Z_4}\right\} \quad (18)$$

$$V_{LSE} = \frac{I_S}{2(A*B - C^2)} * \frac{Z_3 - Z_4}{Z_0 Z_C + Z_3 Z_4} \quad (19)$$

$$V_{LSL} = \frac{I_S}{2(A*B - C^2)} * \frac{Z_1 - Z_2}{Z_0 Z_L + Z_1 Z_2} \quad (20)$$

In Eq. (17), V_{LC} is the common mode voltage caused by a switching regulator and a CPU clock oscillator, V_{LSE} is the signal's common mode voltage caused by the unbalance of the telecommunications equipment, and V_{LSL} is the signal's common mode voltage caused by the unbalance of the telecommunications line. Equation (17) shows that the signal's common mode voltage is generated by the unbalance of the line connected to the equipment as well as the equipment unbalance.

3.2 Relation between Signal's Common Mode Voltage and LCL

The Impedance Stabilization Network (ISN) for measuring the interference voltage at telecommunications signal ports represents the common mode input impedance of the telecommunications line and usually has a large LCL value[6]. Therefore, the signal's common mode voltage is scarcely affected by connecting the ISN to the signal ports. That means that $V_{LSL} \ll V_{LSE}$. Therefore, only V_{LC} and V_{LSE} are measured by the ISN. To estimate the V_{LSL} from the signal's differential mode voltage and the LCL of the line, let F_{AL} denote the conversion factor that expresses the relation between the signal's differential mode voltage and signal's common mode voltage due to the unbalance of the line. The conversion factor, F_{AL}, is defined by

$$F_{AL} = V_S / V_{LSL} \quad (21)$$

The equipment unbalance as well as the line unbalance are usually represented by LCL. Therefore, the rela-

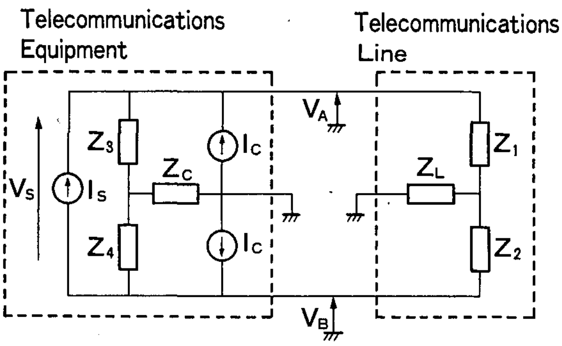

Fig. 5 An equivalent circuit of the network composed of telecommunications equipment and line.

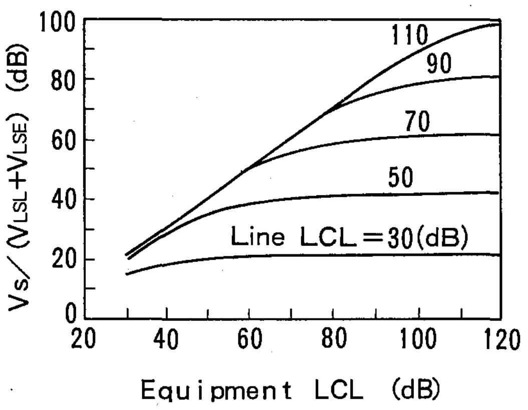

Fig. 6 Relation between the factor of differential/common mode voltage [$V_S/(V_{LSL}+V_{LSE})$] and the LCL of the equipment.

tion between the conversion factor and the LCL is evaluated.

When the equivalent circuit shown in Fig. 5 is evaluated with respect to the LCL of the equipment (LCL_E) or the LCL of the line (LCL_L), the LCLs are given by[9]

$$LCL_E(\text{dB})=20\log\left\{\frac{(Z_3-Z_4)^2+2Z_0(2Z_0+4Z_c)}{2Z_0(Z_3-Z_4)}\right\} \tag{22}$$

$$LCL_L(\text{dB})=20\log\left\{\frac{(Z_1-Z_2)^2+2Z_0(2Z_0+4Z_L)}{2Z_0(Z_1-Z_2)}\right\} \tag{23}$$

Equations (20), (22) and (23) are used to calculate the relation between the factor of signal's differential/common mode voltage and the LCL of the equipment. The results are plotted in Fig. 6. In those calculations, $Z_0=100$ ohms, $Z_C=1000$ ohms and $Z_L=125$ ohms are selected as typical values. The LCLs of the equipment and the line are controlled by the ratios Z_1/Z_2 and Z_3/Z_4. Figure 6 shows that the factor is mostly dependent on the LCL of the line when the LCL of the equipment is larger than that of the line.

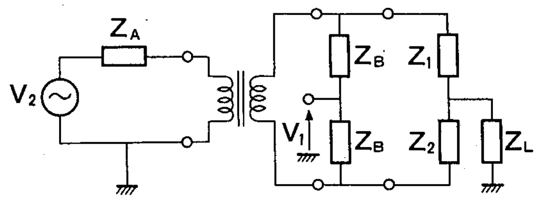

Fig. 7 Experimental setup for measuring the relation between the conversion factor and the LCL of the line.

When a number of devices are connected to a telecommunications line, such as in ISDN bus connection, the LCL of the line is usually lower than that of the equipment[8]. Therefore, it is possible to regard the signal's common mode voltage to be mostly dependent on the LCL of the line connected to the equipment.

3.3 Approximation

In ordinary telecommunications systems, $I_C \ll I_S$, $Z_3-Z_4 \ll Z_0$ can be assumed; when a signal is being transmitted on a balanced pair line, $Z_1-Z_2 \ll Z_0$ can also be assumed. Then, from Eqs. (11) and (23), V_S and LCL_L are approximated by

$$V_S=\frac{I_S}{2(A*B-C^2)}\left\{\frac{Z_0}{Z_0Z_L+Z_1Z_2}+\frac{Z_0}{Z_0Z_C+Z_3Z_4}\right\} \tag{24}$$

$$LCL_L(\text{dB})=20\log\{(2Z_0+4Z_L)/(Z_1-Z_2)\} \tag{25}$$

From Eq. (20) and Eq. (24), F_{AL} is approximated by

$$F_{AL}=2\frac{Z_0*(Z_C+Z_L)+Z_1Z_2+Z_3Z_4}{(Z_1-Z_2)*(Z_C+Z_3Z_4/Z_0)} \tag{26}$$

When $Z_C \gg Z_0$ and $Z_C \gg Z_L$ can be assumed, Eq. (25) can be approximated with

$$F_{AL}=2Z_0/(Z_1-Z_2) \tag{27}$$

Using Eqs. (24), (25) and (26), the relation between the signal's common mode voltage V_{LSL} and the LCL_L is given by

$$V_{LSL}(\text{dB})=V_S(\text{dB})-LCL_L(\text{dB})+20\log(1+Z_L/Z_0) \tag{28}$$

An experiment was carried out to confirm the validity of the approximation. The setup for the experiment is shown in Fig. 7. A transformer whose LCL is large enough compared to that of the line is connected to the line. A circuit constructed with Z_1, Z_2 and Z_L is used to simulate a telecommunications line. $Z_L=125$ ohms and $Z_1+Z_2=100$ ohms are selected as typical values. A circuit constructed with Z_B is used to measure the voltage between the wires and the ground. $Z_B=1000$ ohms is selected to satisfy

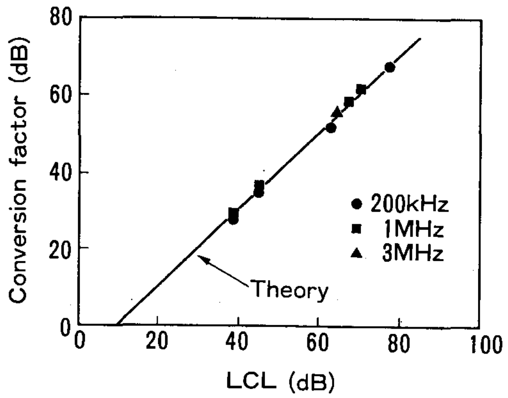

Fig. 8 Relation between the conversion factor and the LCL of the line.

the condition, $2Z_B \gg Z_1+Z_2$.

Signals of 200 kHz, 1 MHz and 3 MHz are supplied to the simulated line through the transformer, and the conversion factor F_{AL} is measured. The LCL of the line, LCL_L, is set by the ratio of Z_1 and Z_2, and its value is measured using the circuit shown in Fig. 2. Figure 8 shows the calculated and measured results of the relation between the conversion factor F_{AL} and the LCL of the line, LCL_L. Figure 8 shows that good agreement is obtained between the calculated and measured values. Consequently, the validity of the approximation mentioned above is confirmed and the signal's common mode voltage caused by the line unbalance can be evaluated by Eq. (28).

4. Method of Measuring the Signal's Common Mode Voltage

4.1 Circuit for Measurement

The interference voltages at the telecommunications signal ports are usually measured by an Impedance Stabilization Network (ISN). An ISN for measuring both the signal's common mode voltage and the common mode voltage caused by the switching regulator and the clock oscillator is investigated (Fig. 9). In Fig. 9, circuit P_1 is an ISN generally used for measuring V_{LC} and V_{LSE}, and circuit P_2 is the circuit for measuring V_{LSL}. In circuit P_1, C_5, Z_5 and T_1 simulate the common mode impedance between the telecommunications line and the ground; T_2 is a common mode choke coil for decoupling the interference originating in the host equipment; J_1 is the terminal for measuring the common mode voltage. In circuit P_2, C_6 and Z_6 are components for attainning high-impedance and DC cutting to avoid influencing the signal transmission; T_3 is a transformer for impedance-matching with the measurement receiver; J_2 is the terminal for measuring the differential mode voltage.

Since circuit P_1 is designed to make the LCL of

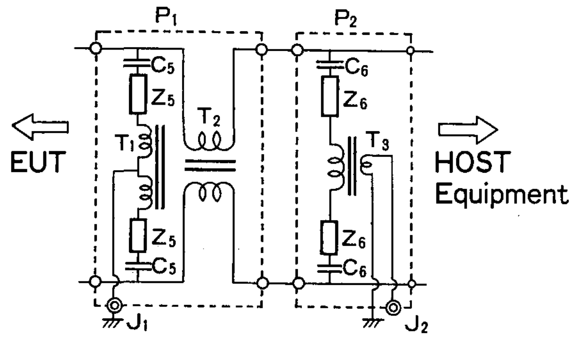

Fig. 9 Impedance Stabilization Network for measuring both the common mode voltage and signal's differential mode voltage.

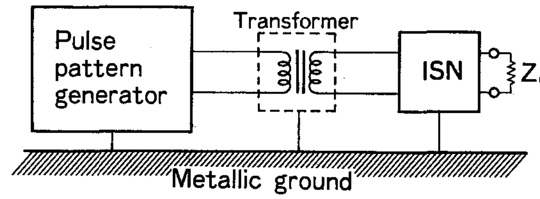

Fig. 10 Experimental layout for confirming the measurement method.

the circuit larger than that of the equipment to be tested, V_{LSE} is larger than V_{LSL}. Therefore, only $V_{LC} + V_{LSE}$ can be measured by circuit P_1. V_{LSL} is obtained by the following procedure.

(1) The differential mode voltages are measured using circuit P_2.

(2) The Z_0 and LCL values are determined from the specifications of the telecommunications system to be tested.

(3) The Z_L value is determined from the specifications of the ISN.

(4) The signal's common mode voltage is calculated using Eq. (28).

4.2 Measurement

A measurement was carried out to confirm the measurement method. The test setup for the experiment is shown in Fig. 10. A pulse pattern generator and a transformer which has a large LCL simulate the telecommunications equipment to be tested. In Fig. 10, 160 kb/s pseudo-noise sequence bipolar pulses are supplied to the ISN through the transformer by the pulse pattern generator. Two types of ISNs are used in the experiment. One is the ISN shown in Fig. 9, labeled ISN-A, and the other is the generally used ISN which is the same circuit as circuit P_1 shown in Fig. 9, labeled ISN-B. Though ISN-B originally has a large LCL, the LCL of ISN-B is intentionally tuned to 40 dB by modifying one of the symmetrical impedance Z_5 so as to examine the signal's common mode compo-

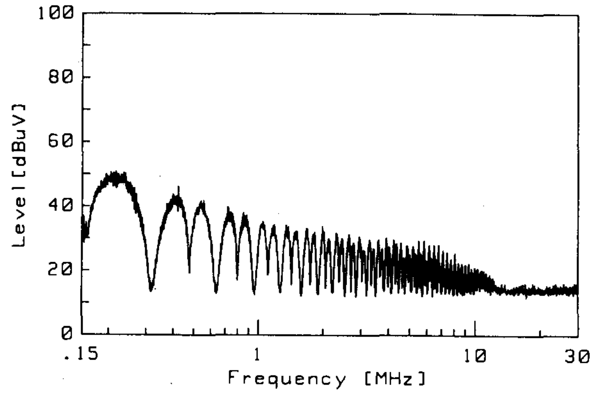

Fig. 11 Common mode voltages measured by ISN-A.

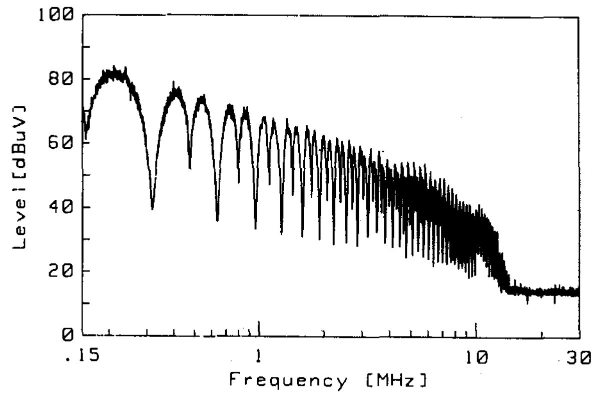

Fig. 12 Common mode voltages measured by ISN-B.

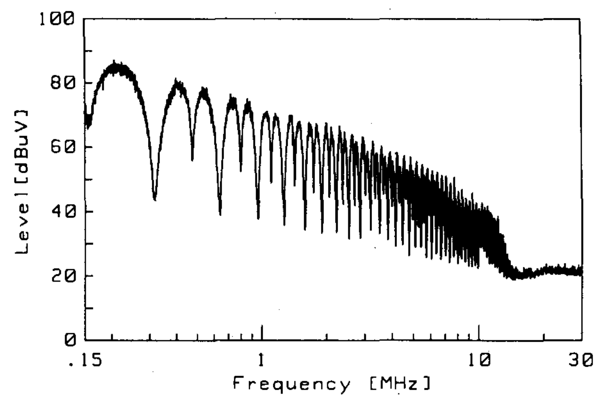

Fig. 13 The signal's common mode voltages calculated from the signal's differential mode voltage.

nent caused by the line unbalance in the experiment. Where 40 dB is the worst LCL for telecommunications line in the ISDN basic access system[9].

The common mode voltages are measured and the signal's common mode voltage is evaluated using two types of ISNs. The results are shown in Figs. 11 to 13. Figures 11 and 12 show the common mode voltages measured by ISN-A and ISN-B. Figure 13 shows the signal's common mode voltage calculated from the signal's differential mode voltage measured by ISN-A. The parameters of $Z_0=100$ ohms, $Z_L=125$ ohms and $LCL=40$ dB are used for the experiment as well as for the calculation of the signal's common mode voltage using Eq. (28). Figures 11 to 13 confirm the following points.

(1) The common mode voltages measured by ISN-A are lower than the voltages measured by ISN-B. The results show that the common mode voltage levels measured by the usual ISN are erroneous when the LCL of the line is lower than that of ISN.

(2) The signal's common mode voltage calculated from the signal's differential mode voltage closely agrees with the common mode voltages measured by ISN-B, and the calculation error is less than 3 dB. This means that the signal's common mode voltage caused by the line unbalance can be evaluated from the signal's differential mode voltage.

When a large amount of equipment is connected to the same telecommunications line, the LCL of the line is lower than that of each piece of equipment. In that case, it is necessary to take into consideration the signal's common mode voltage to evaluate the exact interference level. The proposed method of measuring the signal's common mode voltage is effective since the quasi-peak or average interference level varies with the pulse pattern transmitted, making it difficult to calculate the quasi-peak or average interference level including the signal's common mode voltage.

5. Conclusion

In this paper, we have considered a method for estimating the interference due to unbalance in telecommunications line. First, we showed that the unbalance of the telecommunications line causes interference to radio receivers by an experiment using overhead cable. Second, the interference-inducing mechanism was clarified using an equivalent circuit of a network composed of telecommunications equipment and line. The conversion factor between the signal's differential and common mode voltages is obtained analytically, and the relation between the conversion factor and the LCL of the line is experimentally confirmed. Finally, an ISN for measuring both the signal's common mode voltage and the common mode voltages generated by the switching regulator and the clock oscillator is proposed on the basis of this investigation. An experiment using the proposed ISN shows that the estimation error is less than 3 dB.

As a result, a method for estimating the common mode voltages at telecommunications signal ports, including the signal's common mode component, is obtained. In the future, the measurement accuracy should be improved.

Acknowledgment

The authors would like to thank Dr. Koichi

Asatani and Dr. Masamitsu Tokuda for their guidance and encouragement.

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