Influence of an AC-coaxial adapter on measurements of the AMN impedance

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Abstract: The measurements of the characteristics of an artificial mains network (AMN) are always affected by an AC-coaxial adapter connecting an impedance measuring equipment to the AMN. The present paper theoretically investigates the influences of the adapter on the measured AMN S-parameters in terms of the mode S-parameters. As a result, it proposes a correction method for eliminating the adapter influences in order to reveal the true AMN characteristics. The experimental measurements using two adapters of considerably different characteristics prove that the proposed method can yield almost the same estimates of the AMN impedance.

Keywords: AMN, artificial mains network, conducted disturbance, EMC measurement

Classification: Energy in Electronics Communications

References

- [1] CISPR 16-1-2, ed. 1.2: *Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-2 Radio disturbance and immunity measuring apparatus - Ancillary equipment - Conducted disturbances*, 2006.
- [2] T. Williams and G. Orford, *Calibration and use of artificial mains networks and absorbing clamps*, Report DTI-NMSPU project FF2.6, Schaffner-Chase EMC Ltd., 1998.
- [3] M. Borsero, C. Pravato, A. Sona, M. Stellini, and A. Zuccato, “Improved adapters for the accurate calibration of LISN input impedance,” *Proc. 18th Int’l Zurich Symp. on EMC (EMC Zurich 2007)*, pp. 489–492, 2007. DOI:10.1109/EMCZUR.2007.4388302
- [4] A. Sugiura and Y. Kami, “Generation and propagation of common-mode currents in a balanced two-conductor line,” *IEEE Trans. Electromagn. Compat.*, vol. 54, no. 2, pp. 466–473, April 2012. DOI:10.1109/TEMC.2011.2162523
- [5] D. E. Bockelman and W. R. Eisenstadt, “Combined differential and common-mode scattering parameters: theory and simulation,” *IEEE Trans. Microw. Theory Techn.*, vol. 43, no. 7, pp. 1530–1539, July 1995. DOI:10.1109/22.392911

1 Introduction

Radio interference potential of electric/electronic equipment in the frequency range from 9 kHz to 30 MHz is usually evaluated by the voltage measurements of the conducted disturbances emitted from the equipment into the mains cable, as shown in Fig. 1. In these measurements, an artificial mains network (AMN) is used to make a measuring receiver indicate the disturbance voltage across each wire of the mains cable of the equipment under test (EUT) and a reference ground plane that is connected to the chassis of the AMN. Thus, the disturbance voltage measurements are seriously affected by the impedance appearing across an EUT terminal of the AMN and the reference ground that is called the AMN impedance [1]. Since the EUT terminals of an AMN are in an AC power socket, an AC-coaxial adapter is required for the connection between the AMN and an impedance measuring equipment for the AMN impedance measurement. Various studies have been conducted on the structure of the adapter [2, 3], but the influences of the adapter on the AMN impedance measurement have not been rigorously investigated.

Fig. 1. Conducted disturbance measurement using an AMN

2 AC-coaxial adapter

Two different types of AC-SMA adapters, A and B, were experimentally designed and made by REPIC Co. and Kyoritsu Technology Co., respectively, for investigations of the AMN impedance measurements, as shown in Fig. 2(a). Both adapters have two SMA receptacles, where each receptacle is connected to one of the AC plug blades. Usually the protective earth (PE) pin of the AC plug makes the electrical contact with the AMN chassis. We assume that the AC plug blades with the PE pin form a balanced two-conductor parallel line. Thus, the adapter can be regarded as a 4-port network: the input ports are the two SMA receptacles and the output ports are the two AC plug blades in combination with the PE pin.

The characteristic impedance of the SMA section of the adapter is 50Ω , while that of the AC plug section is unknown. However, we tried to determine the 4-port S-parameters of the AC-SMA adapter including the AC plug section for a reference impedance of 50Ω . This means that the two output ports are terminated using imaginary transmission lines with a characteristic impedance of 50Ω as depicted in Fig. 2(b). Since the adapter is balanced with respect to the PE line or the reference ground, the port voltages/currents (V_1 , V_2 , I_1 , & I_2) can be expressed in terms of the mode voltages/currents (V_d , V_c , I_d , & I_c) in the following way:

$$\begin{pmatrix} V_1 \\ V_2 \end{pmatrix} = \begin{pmatrix} 1/2 & 1 \\ -1/2 & 1 \end{pmatrix} \begin{pmatrix} V_d \\ V_c \end{pmatrix} \equiv (T_V) \begin{pmatrix} V_d \\ V_c \end{pmatrix},$$

$$\begin{pmatrix} I_1 \\ I_2 \end{pmatrix} = \begin{pmatrix} 1 & 1/2 \\ -1 & 1/2 \end{pmatrix} \begin{pmatrix} I_d \\ I_c \end{pmatrix} \equiv (T_I) \begin{pmatrix} I_d \\ I_c \end{pmatrix}, \quad (1)$$

where subscripts “*d*” and “*c*” represent the differential- and common-modes. Since the adapter is well-balanced, it can be assumed that conversion between the differential- and common-modes barely occurs in the adapter [4]. Therefore, although the two modes are usually treated simultaneously using the mix-mode S-parameters [5], the present paper deals with these modes independently. The symmetrical nature of the equivalent circuit shown in Fig. 2(b) implies that the characteristics of the adapter in each mode can be described by using two mode S-parameters, S_{rAA}^S and S_{rBA}^S , as shown in Fig. 2(c). The superscript “*S*” refers to a single adapter. Subscript “*r*” is replaced by “*d*” for the differential-mode and “*c*” for the common-mode. Subscripts “*A*” and “*B*” represent the input and output reference planes. Z_r is the reference impedance for mode *r*.

Fig. 2. Mode S-parameters of the AC-SMA adapter and the AMN

3 S-parameters of a back-to-back pair of adapters

The mode S-parameters of a back-to-back pair of the adapters referenced in Fig. 2(d) can be expressed as

$$\begin{aligned} S_{rCA}^P &= \frac{S_{rBA}^S{}^2}{1 - S_{rAA}^S{}^2} \\ S_{rAA}^P &= S_{rAA}^S + \frac{S_{rBA}^S{}^2 S_{rAA}^S}{1 - S_{rAA}^S{}^2} = S_{rAA}^S (1 + S_{rCA}^P) \end{aligned} \quad r = d \text{ or } c, \quad (2)$$

where superscript “*P*” represents the back-to-back pair and subscript “*C*” represents the reference plane of the pair output. Therefore, the mode S-parameters of a single adapter can be easily calculated from those of the back-to-back pair by using

$$\begin{aligned} S_{rAA}^S &= \frac{S_{rAA}^P}{1 + S_{rCA}^P} \\ S_{rBA}^S &= \sqrt{S_{rCA}^P (1 - S_{rAA}^S{}^2)} \end{aligned} \quad r = d \text{ or } c. \quad (3)$$

4 Relationship between the port and mode S-parameters

The S-parameters in the mode expression are hypothetical quantities and are different from the S-parameters actually measured at the ports using a network analyzer. Therefore, it is necessary to develop the relationship between the mode S-parameters and the port S-parameters for a back-to-back pair of adapters.

This paragraph deals with a more general 4-port circuit containing two input ports (reference plane “*I*”) and two output ports (reference plane “*O*”). When a signal source (electromotive force E_0 and impedance Z_0) is connected to one of the input ports, Port 1, Eq. (1) yields a pair of the equivalent modal sources with the incident voltage waves and the impedances given by

$$V_{dI}^+ = \frac{E_0}{2}, \quad Z_{dI} = 2Z_0, \quad V_{cI}^+ = \frac{E_0}{4}, \quad Z_{cI} = \frac{Z_0}{2}, \quad (4)$$

where the other ports are terminated in Z_0 . The mode voltages and currents at the input are thus expressed using the modal input reflection coefficient S_{rII} as

$$V_{rI} = (1 + S_{rII})V_{rI}^+, \quad \vec{I}_{rI} = \frac{(1 - S_{rII})}{Z_{rI}} V_{rI}^+ \quad \text{for } r = d \text{ or } c. \quad (5)$$

The actual voltages and currents at input Ports 1 and 2 are given by

$$\begin{aligned} \begin{pmatrix} V_1 \\ V_2 \end{pmatrix} &= (T_V) \begin{pmatrix} V_{dI} \\ V_{cI} \end{pmatrix} = \frac{E_0}{4} \begin{pmatrix} 2 + S_{dII} + S_{cII} \\ -S_{dII} + S_{cII} \end{pmatrix} \\ \begin{pmatrix} \vec{I}_1 \\ \vec{I}_2 \end{pmatrix} &= (T_I) \begin{pmatrix} \vec{I}_{dI} \\ \vec{I}_{cI} \end{pmatrix} = \frac{E_0}{4Z_0} \begin{pmatrix} 2 - S_{dII} - S_{cII} \\ S_{dII} - S_{cII} \end{pmatrix}. \end{aligned} \quad (6)$$

Then, the incident and reflected voltage waves at the input ports are described as

$$\begin{aligned} V_1^+ &= \frac{V_1 + Z_0 \vec{I}_1}{2} = \frac{E_0}{2}, \quad V_1^- = \frac{V_1 - Z_0 \vec{I}_1}{2} = \frac{E_0}{4} (S_{dII} + S_{cII}) \\ V_2^- &= \frac{V_2 - Z_0 \vec{I}_2}{2} = \frac{E_0}{4} (-S_{dII} + S_{cII}) \end{aligned} \quad (7)$$

Similar expressions for output Ports 3 and 4 are derived in terms of S_{rII} and S_{rOI} . Thus, the S-parameters measured at the four ports, S_{iI} ($i = 1, 2, 3, 4$), are related with the mode S-parameters, S_{rII} and S_{rOI} , in the following forms:

$$\begin{aligned} S_{11} &\equiv \frac{V_1^-}{V_1^+} = \frac{S_{dII} + S_{cII}}{2}, \quad S_{21} \equiv \frac{V_2^-}{V_1^+} = \frac{-S_{dII} + S_{cII}}{2} \\ S_{31} &\equiv \frac{V_3^-}{V_1^+} = \frac{S_{dOI} + S_{cOI}}{2}, \quad S_{41} \equiv \frac{V_4^-}{V_1^+} = \frac{-S_{dOI} + S_{cOI}}{2}. \end{aligned} \quad (8)$$

The above equations can be rewritten as

$$\begin{aligned} S_{dII} &= S_{11} - S_{21}, & S_{dOI} &= S_{31} - S_{41} \\ S_{cII} &= S_{11} + S_{21}, & S_{cOI} &= S_{31} + S_{41} \end{aligned} \quad (9)$$

5 AMN S-parameters

The circuits of the phase and neutral power lines in the AMN are designed to be independent but have the same characteristics [1]. Only one receiver port is provided for connecting a measuring receiver (input port: 50 Ω) to one of the phase and neutral lines by a switch. The other power line is connected to a 50- Ω load instead of the receiver. Accordingly, the AMN can be regarded as a well-balanced network where mode conversion does not occur [4].

The S-parameters of an AMN are measured using an AC-SMA adapter that is attached to the EUT terminals of the AMN. The SMA receptacles are numbered Ports 1 and 2. The AMN receiver port is named Port 3, where its reference plane is denoted as “C”. The measured data on the port S-parameters S^m_{ij} may differ from the true values of the S-parameters of the AMN alone, S^N_{ij} , due to the influence of the adapter. Since Port 4 does not exist in the AMN, measurements are required for S^m_{32} instead of S^m_{41} . The measured S-parameters S^m_{ij} are converted into the mode S-parameters S^m_{rAA} and S^m_{rCA} by using Eq. (9) where S^m_{41} is replaced by S^m_{32} . Referring to Fig. 2(e), S^m_{rAA} and S^m_{rCA} can be related to the mode S-parameters of the AMN alone and those of the single adapter in the following way:

$$\begin{aligned} S^m_{rAA} &= S^S_{rAA} + \frac{S^S_{rBA}{}^2}{1 - S^S_{rAA}S^N_{rBB}} S^N_{rBB} \\ S^m_{rCA} &= S^m_{rAC} = \frac{S^S_{rBA}S^N_{rCB}}{1 - S^S_{rAA}S^N_{rBB}} \end{aligned} \quad \text{for } r = d \text{ or } c. \quad (10)$$

Thus, Eqs. (9) and (10) yield the estimates of the true mode S-parameters of the AMN alone from the measured data on the port S-parameters as

$$\begin{aligned} S^N_{dBB} &= \frac{S^m_{11} - S^m_{21} - S^S_{dAA}}{S^S_{dBA}{}^2 + (S^m_{11} - S^m_{21})S^S_{dAA} - S^S_{dAA}{}^2} \\ S^N_{cBB} &= \frac{S^m_{11} + S^m_{21} - S^S_{cAA}}{S^S_{cBA}{}^2 + (S^m_{11} + S^m_{21})S^S_{cAA} - S^S_{cAA}{}^2} \\ S^N_{dCB} &= \frac{(S^m_{31} - S^m_{32})(1 - S^S_{dAA}S^N_{dBB})}{S^S_{dBA}} \\ S^N_{cCB} &= \frac{(S^m_{31} + S^m_{32})(1 - S^S_{cAA}S^N_{cBB})}{S^S_{cBA}} \end{aligned} \quad (11)$$

Finally, the true values of the AMN port S-parameters, S^N_{ij} , can be estimated by substituting the results of Eq. (11) into Eq. (8).

6 Accurate estimate of the AMN impedance

In conclusion, the estimates of the AMN port S-parameters without the influence of an AC-SMA adapter can be obtained using the following method:

- (i) Two identical AC-SMA adapters are required. Measure the port S-parameters of a back-to-back pair of the adapters, S^P_{i1} , and calculate the mode S-parameters

ters of a single adapter, S_{rAA}^S and S_{rCA}^S , using Eqs. (9) and (3).

- (ii) Measure the port S-parameters of the AMN, S_{ij}^m , with the AC-SMA adapter and calculate the estimates of the port S-parameters of the AMN alone, S_{ij}^N , by using Eqs. (11) and (8).

To demonstrate the validity of the above method, the port S-parameters S_{ij}^m of an AMN were measured using adapters A and B, as shown in Fig. 2(a), and the estimates of S_{ij}^N were calculated following the proposed procedures. The AMN impedances were evaluated for each adapter using

$$Z_{meas} = Z_0 \frac{1 + S_{11}^m}{1 - S_{11}^m}, \quad Z_{estim} = Z_0 \frac{1 + S_{11}^N}{1 - S_{11}^N}. \quad (12)$$

The results are shown in Fig. 3 where the AMN impedances are plotted as the deviations from the specified CISPR 16-1-2 values. Differences between the measured and estimated values at frequencies above 3 MHz may be attributed to parasitic inductance in the adapter, while differences at about 0.01 MHz may be caused by parasitic capacitance. Fig. 3 clearly demonstrates that the AMN impedances given by the measured S-parameters S_{ij}^m greatly depend on the characteristics of the adapter. However, the estimated S-parameters S_{ij}^N yield almost the same AMN impedances regardless of the adapter characteristics. Adapter A is considered to be much better than Adapter B because the measured AMN impedances are closer to the estimated ones.

Fig. 3. Deviation of measured and estimated Z_{AMN} from CISPR specifications

7 Conclusion

The measurements of the AMN characteristics are always affected by the AC-coaxial adapter used to connect an impedance measuring equipment to the AMN. The present paper, therefore, theoretically investigated the influences of the adapter on the measured AMN S-parameters in terms of the mode S-parameters. As a result, a correction method was proposed for eliminating the adapter influences in order to reveal the true AMN characteristics. The experimental measurements using two adapters proved that the proposed method could yield almost the same results on the AMN impedance despite of the considerably different adapter characteristics.