Letters

A Noise Source Impedance Extraction Method for Operating SMPS Using Modified LISN and Simplified Calibration Procedure

Xiaofan Shang, Donglin Su, Hui Xu, and Zhenzhen Peng

***Abstract*—A noise source impedance extraction method for switched-mode power supply (SMPS) under operating condition is proposed and validated in this letter. First, a simplified precalibration method using several known impedances is introduced to eliminate the influence of measurement instruments and other parasitic effects. Second, the configuration of the proposed method is presented and the calculation methods of common-mode and differential-mode noise source impedances using microwave transmission analysis are described, respectively. The experimental results show that the proposed method can extract the noise source impedance of SMPS in wide frequency band with sufficient accuracy. Compared with traditional methods, the complex calibration process can be simplified, and no more additional equipment is required. Moreover, a novel multiple-function line impedance stabilization network (MF-LISN) with the function of electromagnetic interference measurement and noise source impedance extraction is designed according to the proposed method. Since only MF-LISN is used, it can be more convenient to extract the noise source impedance of SMPS for electromagnetic compatibility pretest.**

***Index Terms*—Electromagnetic conductive interference, impedance measurement, switched-mode power supplies (SMPS).**

I. Introduction

Conducted emission control of switched-mode power supply (SMPS) from tens of kHz to 30 MHz to meet the electromagnetic compatibility (EMC) regulations is a vital work in SMPS design procedure, and electromagnetic interference (EMI) filter is an effective way to conducted emission control [1]. However, since the noise source impedance of SMPS under operating condition is not 50 Ω, the value of noise source impedance of SMPS under operation condition has great influence on EMI filter designing [2] and EMI behavior modeling [3], [4].

The noise source impedance of SMPS may vary with several parameters such as input current, input line, and other parasitic parameters. Therefore, the impedance of operating SMPS may be different from the impedance of offline SMPS. Online measurement of noise source impedance of an SMPS can bring more accurate and more specific result than offline measurement. An impedance analyzer (IA) can be used to measure the noise source impedance of offline SMPS simply. However, since only dc bias is provided by IA and it may be insufficient, it is hard to guarantee a normal operating state for SMPS. Besides, it may have a risk of damage due to the large current when an IA is directly connected to an operating SMPS.

Some attempts such as resonance method [5] and insert loss method [6] have been introduced several years ago to measure the noise source impedance of SMPS. The resonance method proposed in [5] was used to obtain the noise source impedance by adding resonant inductor in the SMPS port, but there was no clear way to choose a proper value of the insertion impedance. The insert loss method [6] can only obtain the magnitude of impedance directly, and it is impossible to carry out the measurement under the operating conditions.

In [7], an SMPS noise source impedance extraction method using line impedance stabilization network (LISN) and vector network analyzer (VNA) was proposed, in which a standard through-open-short-match (TOSM) calibration procedure was used at the LISN-EUT interface to compensate the effects of LISN and other factors. Since lines between LISN and EUT are not coaxial, the calibration devices need to be customized and the calibration procedure is quite complicate to carry out. Besides, since the inductance of LISN is not large enough below several hundred kilohertz, the power grid may affect the accuracy of SMPS noise source impedance extraction. However, since the standard TOSM calibration procedure cannot be carried out when the power grid is connected, it is difficult to eliminate the influence of the power grid below several hundred kilohertz.

The two-probe method presented in [8]–[10] was presented to measure the noise source impedance of SMPS under operating conditions using a VNA and two current probes. In this method, either known resistors or calibration fixture is required to characterize the current probes and parasitic effect. However, additional current probes that may be unavailable are required in this method, and the injection effect may be poor due to the large transfer impedance of the probes in the low-frequency range. Moreover, some uncertainty may occur, since it is hard to fix current probes in different measurement and calibration process.

Manuscript received July 7, 2016; revised August 7, 2016, September 22, 2016, and October 24, 2016; accepted November 8, 2016. Date of publication November 22, 2016; date of current version February 11, 2017. This work was supported by the National Natural Science Foundation of China under Grant 61427803 and Grant 61521091.

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Digital Object Identifier 10.1109/TPEL.2016.2631578

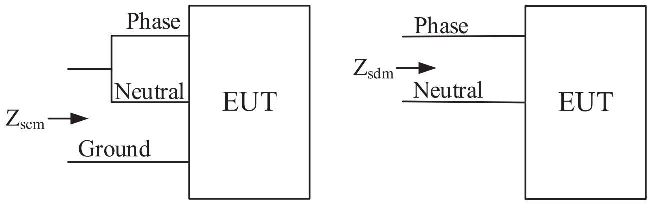


Fig. 1. Physical interpretation for CM and DM noise source impedances.

In addition, there were some online impedance measurement methods proposed in related areas. For example, online measurement of battery impedance at different frequencies is quite important to characterize batteries. And some progresses by utilizing power electronics as the excitation source were proposed to make impedance measurement of battery more convenient below several hundred kilohertz [11]–[13]. In these methods, a testing signal with quite small magnitude is injected, and an oscilloscope is used detection the signal in time domain. When the impedance is large, which may be more than several tens Ω in SMPS, the magnitude of the tested circuit signal is too small to detect in time domain using an oscilloscope. In other words, the methods proposed in [11]–[13] are not suitable for SMPS applications. Moreover, a measurement method for voltage-dependent capacitances of power semiconductor devices using high-voltage dc bias is presented in [14]. However, three current probes are required, and its calibration procedure is similar to the method proposed in [9], which we consider complicated.

A noise source impedance extraction method under operating conditions based on modified LISN and simplified calibration procedure is proposed in this letter. The rest of the letter is organized as follows: Section II reviews the definition of noise source impedance and introduces the proposed measurement and calculation methods for common-mode (CM) and differential-mode (DM) noise source impedances, respectively. A novel modified LISN that can be used for EMC pretest based on the proposed method is shown in Section III, and the experimental validation is also presented. Finally, the conclusions are given in Section IV.

II. Derivation of the Proposed Method

Considering a typical SMPS with phase, neutral, and ground lines, the CM and DM noise source impedances can be defined separately. There are several physical interpretations for CM and DM noise source impedances [6], [15], [16]. Fig. 1 shows the physical interpretation in [6], which we consider as the most straightforward. The CM noise source impedance Z_{scm} is the equivalent impedance between the ground and the terminal, which is formed by shorting phase and neutral lines. The DM noise source impedance Z_{sdm} is the impedance between the phase and neutral lines without the ground current.

It is specified in EMC regulations such as MIL-STD-461 that standard LISNs are required to insert between the power grid and the EUT in a standard CE measurement[17]. All the devices of a standard LISN are specified in the corresponding regulations.

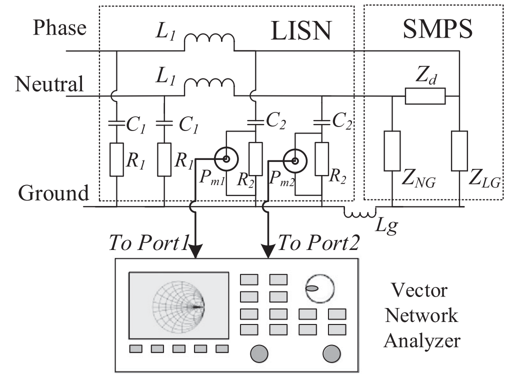


Fig. 2. Measurement configuration of DM noise source impedance.

A. DM Noise Source Impedance Extraction Method

As shown in Fig. 2, Z_d is the impedance between the phase line and neutral line, while Z_{LG} and Z_{NG} are the phase-to-ground and neutral-to-ground impedances. Two LISNs are inserted between the SMPS and power grid by connecting them to phase line and neutral line, respectively. The EMI measurement ports P_{m1} and P_{m2} of the two LISNs are separately connected to *Port1* and *Port2* of a VNA using coaxial lines. The VNA is well calibrated and used to measure the magnitude and phase of *S* parameters of the whole system in the range of measurement frequencies.

An inductor L_g with several millihenry inductance is inserted between the ground line of SMPS and LISN to reduce the ground current in the range of measurement frequencies. Since the parasitic capacitance at high frequencies may make the impedance of the inductor pretty small, an impedance measurement is recommended to ensure that the impedance of L_g is large enough in the whole frequency range.

Moreover, in order to minimize the error that may be caused by the external cables at high frequencies, the cables used in calibration procedure should be the same or similar to the actual cables and the external cables should have a certain distance (e.g., the distance of the two wires is more than five times the radius of the wires) to reduce the proximity effect [18].

Meanwhile, since the impedance of the grid may change with time depending on other equipment on the grid, a stabilized voltage supply is recommended as power supply. With the usage of stabilized voltage supply, other equipment can be controlled to ensure that the impedance of grid stay the same. Under conditions where a stabilized voltage supplies are unavailable, one can reduce the time lapse between calibration and measurement to reduce the impedance change of the power grid.

1) Calibration Procedure: A known impedance Z_m is connected between the EUT ports of two LISNs, instead of SMPS shown in Fig. 2. The equivalent circuit that is divided into three cascade networks is shown in Fig. 3. R_2 and C_2 are the resistor and the capacitor of LISN, respectively. Z_{LC} is the additional impedance caused by L_1, C_1, R_1, and power grid. Z_{set} is the parasitic impedance caused by external cables.

As describe in [19], the *ABCD* parameters of the *Network2* in Fig. 3 are $A_2 = 1$, $B_2 = Z_m$, $C_2 = 0$, and $D_2 = 1$. Since *Network1* and *Network3* are the equivalent circuits of two same

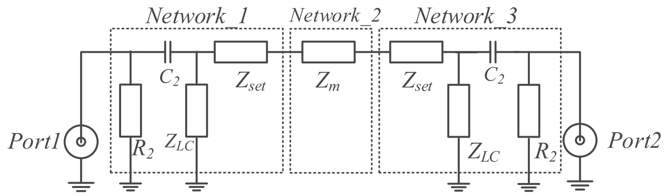


Fig. 3. Equivalent circuit of DM noise source impedance calibration.

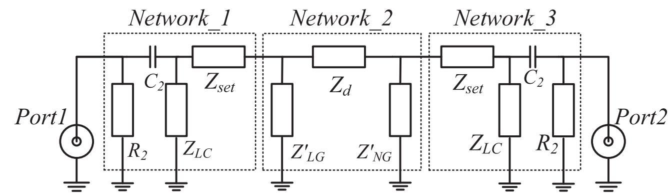


Fig. 4. Equivalent circuit of DM noise source impedance measurement.

LISNs, and the back-to-back connection mode of two LISNs as shown in Fig. 3 guarantees that the *Network1* and*Network3* are mirror symmetrical. Thus, we can obtain $A_1 = D_3$, $B_1 = B_3$, $C_1 = C_3$, and $D_1 = A_3$. The *ABCD* matrix of the whole three cascade networks can be expressed as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} A_3 & B_3 \\ C_3 & D_3 \end{bmatrix}$$
$$= \begin{bmatrix} A_1C_1Z_m + B_1C_1 + A_1D_1 & A_1^2Z_m + 2A_1B_1 \\ C_1^2Z_m + 2C_1D_1 & A_1C_1Z_m + B_1C_1 + A_1D_1 \end{bmatrix} \quad (1)$$

where

$$B = A_1^2 Z_m + 2A_1 B_1 \quad (2a)$$

$$C = C_1^2 Z_m + 2C_1 D_1. \quad (2b)$$

On the other hand, using the *S* parameters measured by VNA and the relationship between *S* parameters and *ABCD* parameters [19], *B* and *C* can be computed as

$$B = Z_0 \frac{(1+S_{11})(1+S_{22}) - S_{12}S_{21}}{2S_{21}} \quad (3a)$$

$$C = \frac{1}{Z_0} \frac{(1-S_{11})(1+S_{22}) + S_{12}S_{21}}{2S_{21}} \quad (3b)$$

where Z_0 is the characteristic impedance of the measurement system.

When two known impedances Z_{m1} and Z_{m2} are connected to the LISNs in turn, the *B* parameter of the whole network shown in (2a) can be written as

$$\begin{cases} B_{Z_{m1}} = A_1^2 Z_{m1} + 2A_1 B_1 \\ B_{Z_{m2}} = A_1^2 Z_{m2} + 2A_1 B_1 \end{cases} \quad (4)$$

where $B_{Z_{m1}}$ and $B_{Z_{m2}}$ are the *B* parameters of the whole network when Z_{m1} and Z_{m2} are connected, respectively. Therefore, the A_1 parameter of the *Network1* can be solved as

$$A_1 = \pm\sqrt{\frac{B_{Z_{m1}} - B_{Z_{m2}}}{Z_{m1} - Z_{m2}}} \quad (5)$$

where $B_{Z_{m1}}$ and $B_{Z_{m2}}$ can be calculated using (3a) and the *S* parameters measured by the VNA.

There are two solutions in (5). Since the measurement configuration can be regarded as a lumped parameter system, the equivalent circuit of *Network1* in Fig. 3 is composed of discrete passive devices. All the real part of *ABCD* parameters of these passive devices are greater than zero; thus, the real part of *A* parameter of *Network1* should be greater than zero. Moreover, if we use the *A* parameter with negative real part, the real part of the calculated noise source impedance will be negative in the whole frequency range, which is not in conformity with the actual situation. Based on the above considerations, we take the solution with the positive real part as A_1.

Substituting (5) into (4), the B_1 parameter of the *Network1* can be expressed as

$$B_1 = \frac{(B_{Z_{m1}} + B_{Z_{m2}}) - A_1^2 (Z_{m1} + Z_{m2})}{4A_1}. \quad (6)$$

Likewise, the C_1 parameter and D_1 parameter of *Network1* can be obtained using (2b) as

$$C_1 = \pm\sqrt{\frac{C_{Z_{m1}} - C_{Z_{m2}}}{Z_{m1} - Z_{m2}}} \quad (7)$$

and

$$D_1 = \frac{(C_{Z_{m1}} + C_{Z_{m2}}) - C_1^2 (Z_{m1} + Z_{m2})}{4C_1} \quad (8)$$

where the $C_{Z_{m1}}$ and $C_{Z_{m2}}$ are the *C* parameters of the whole network when the Z_{m1} and Z_{m2} are connected, respectively. They can be calculated using (3b) and the *S* parameters which are measured by the VNA.

The *ABCD* matrices $\boldsymbol{A_1}$ and $\boldsymbol{A_3}$ of *Network1* and *Network3* can be constructed using (5)–(8).

2) Calculation Method: The equivalent circuit that is also divided as three cascade networks of measurement configuration is shown in Fig. 4. R_2 and C_2 are the resistor and capacitor of LISN, respectively. Z_{LC} is the additional impedance caused by L_1, C_1, R_1, and power grid. Z_{set} is the parasitic impedance caused by external cables. Z'_{LG} and Z'_{NG} are the impedance caused by Z_{LG}, Z_{NG} and ground inductor L_g, respectively.

We use $\boldsymbol{A_1}$, $\boldsymbol{A_2}$, and $\boldsymbol{A_3}$ to represent the *ABCD* matrices of *Network1*, *Network2*, and *Network3*, respectively. The *ABCD* matrix of the whole network can be calculated as $\boldsymbol{A = A_1 A_2 A_3}$.

Since the *ABCD* matrices $\boldsymbol{A_1}$ and $\boldsymbol{A_3}$ are obtained in calibration procedure, the *ABCD* matrix of *Network2* can be calculated as

$$\boldsymbol{A_2 = A_1^{-1} A A_3^{-1}} \quad (9)$$

where $\boldsymbol{A_1^{-1}}$ and $\boldsymbol{A_3^{-1}}$ are the inverse matrices of $\boldsymbol{A_1}$ and $\boldsymbol{A_3}$.

Since *Network2* is a typical π-mode circuit, the impedance Z_d can be calculated as $Z_d = B_2$ using the relation between the impedance and *ABCD* matrix[19]. As mentioned before, the DM noise source impedance Z_{sdm} is the impedance between the phase and neutral lines without the ground current. In the proposed method, since an inductor L_g shown in Fig. 2 is inserted between the ground line of SMPS and LISNs, the impedances Z'_{LG} and Z'_{NG} as shown in Fig. 4 can be several hundred ohms to

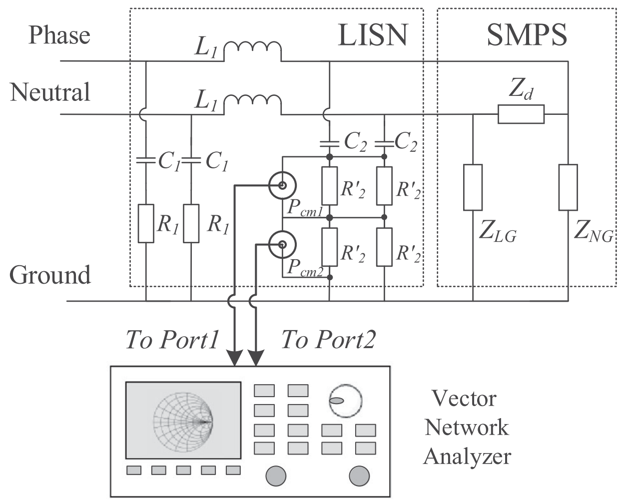


Fig. 5. Diagram of the modified LISNs and CM noise source impedance measurement configuration.

several hundred kiloohms in the frequency range of 100 kHz to 30 MHz. While the DM noise source impedance is typically tens of ohms to hundreds of ohms in the same frequency range, the ground current can be regarded sufficiently small [6]. Therefore, we can use the calculated $Z_d = B_2$ to estimate the DM noise source impedance Z_{sdm}.

B. CM Noise Source Impedance Extraction Method

1) Modification of LISN and Measurement Configuration: As shown in Fig. 5, we substitute the resistor R_2 of LISN into two equal series resistors $R_2' = 1/2R_2$ and connect the resistors R_2' of two LISNs. Two new coaxial ports named $P_{\mathrm{cm}1}$ and $P_{\mathrm{cm}2}$ are also connected. $P_{\mathrm{cm}1}$ and $P_{\mathrm{cm}2}$ are connected together as Fig. 5 and the two ports are connected to the two LISNs. The diagram of modified LISN and CM noise source impedance measurement configuration is shown in Fig. 5. The coaxial ports $P_{\mathrm{cm}1}$ and $P_{\mathrm{cm}2}$ of two LISNs are separately connected to Port1 and Port2 of a VNA. The VNA is well calibrated and used to measure the magnitude and phase of *S* parameters of the whole system in the range of measurement frequencies.

The CM noise source impedance is the equivalent impedance between the ground and the terminal, which is formed by shorting phase and neutral lines. As shown In Fig. 5, since the connection of R_2' in two LISNs, the phase and neutral terminals can be regarded as connected. Moreover, since the CM noise impedance is usually large enough, shorting the phase and neutral terminals or not makes little difference [6].

Based on the above considerations, if we consider the system between the P_{cm1} and P_{cm2} in Fig. 5, the equivalent circuit is shown in Fig. 6. Z_{scm} is the CM equivalent impedance formed by Z_{LG} and Z_{NG} in Fig. 5, and Z_{1l}' and Z_{2l}' are the equivalent parallel impedances of P_{cm1} and P_{cm2}, respectively. Z_{set} in Fig. 6 mainly represents the impedance of capacitor C_2, the impedance caused by ground line, and the impedance caused by phase line and neutral line in Fig. 5. Since these three additional impedances are connected in series with CM noise source impedance, only one Z_{set} is necessary to simplify the calibration procedure. Z_{LC}'

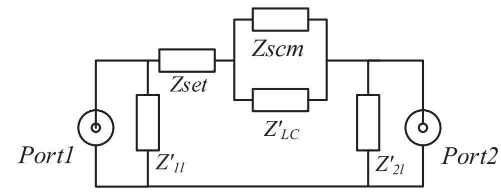


Fig. 6. Equivalent circuit of CM noise source impedance measurement.

is the parallel additional impedance caused by L_1, C_1, R_1, and power grid.

2) Calibration Method and Calculation Method: Since the equivalent circuit in Fig. 6 is a generalized π-mode circuit, the *B* parameter of the network can be calculated as follows:

$$B = Z_{\mathrm{set}} + \frac{Z_{\mathrm{scm}} Z_{LC}'}{Z_{\mathrm{scm}} + Z_{LC}'} \tag{10}$$

where the *B* parameter can be calculated by the measured *S* parameters under the configuration using (3a).

A calibration is implemented to obtain the values of Z_{set} and Z_{LC}' using the CM noise source impedance measurement configuration, as shown in Fig. 5. First, the phase line and neutral line are connected at the LISN and EUT interface. Second, two known impedances Z_{m1} and Z_{m2} are connected between the two lines and ground line, respectively. Meanwhile, similar to considerations about the change of power grid in DM calibration part, a stabilized voltage supply is recommended as power supply. Thus, (10) can be written as

$$\begin{cases} B_{m1} = Z_{\mathrm{set}} + \dfrac{Z_{m1} Z_{LC}'}{Z_{m1} + Z_{LC}'} \\ B_{m2} = Z_{\mathrm{set}} + \dfrac{Z_{m2} Z_{LC}'}{Z_{m2} + Z_{LC}'}. \end{cases} \tag{11}$$

Solving the equations in (11), the Z_{LC}' and Z_{set} can be obtained. It should be noted that there may be multiple solutions since the equations are not linear. The solution with the positive real part is taken as the calibration values of Z_{LC}' and Z_{set} .

To measure the CM noise source impedance Z_{scm} of an SMPS, the SMPS is connected to the modified LISNs, as shown in Fig. 5. The *S* parameters can be measured using the VNA, and the transmission parameter B_x of the whole network can be calculated using (3a). The CM noise source impedance Z_{scm} can be calculated by substituting the values of B_x, Z_{LC}', and Z_{set} into (10) as

$$Z_{\mathrm{scm}} = \frac{(B_x - Z_{\mathrm{set}}) Z_{LC}'}{Z_{LC}' - (B_x - Z_{\mathrm{set}})}. \tag{12}$$

III. Multiple-Function LISN and Experimental Validation

We have designed a new type LISN named multiple-function LISN (MF-LISN) by modifying standard LISN based on the principle mentioned in Section II. With an additional VNA, the MF-LISN can be used for EMI measurement as well as DM and CM noise source impedances extraction by simple manual switching. For a three-line system, the circuit schematic diagram and the photo of the prototype of MF-LISN by modifying the standard LISN specified in [17] are shown in Fig. 7. Four coaxial

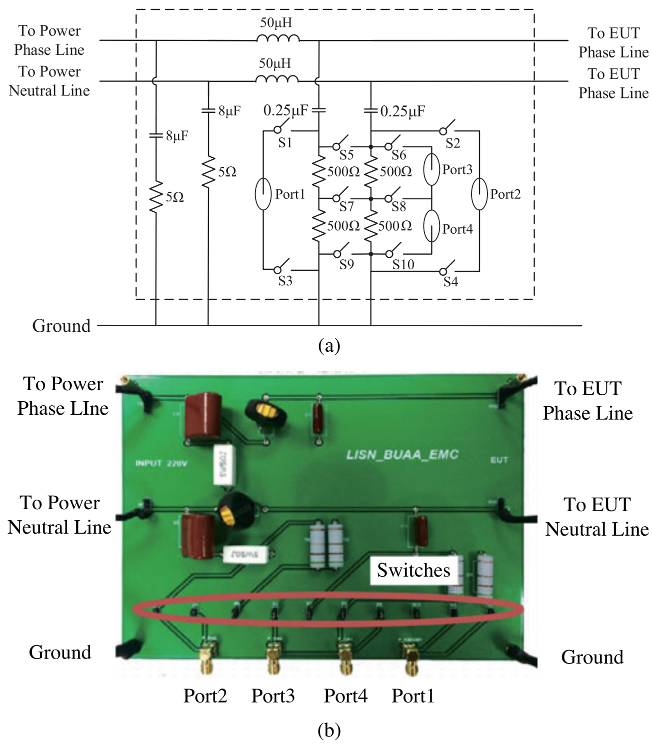


Fig. 7. (a) Circuit schematic diagram of proposed equipment. (b) Photo of the prototype of proposed equipment.

ports and several manual switches are provided in the MF-LISN to configure different mode measurements.

A. Experimental Validation Using Passive Resistor Network

Using passive resistors and *LRC* networks to validate the effectiveness of the proposed method and the new designed MF-LISN, the Keysight E5080A VNA was used to measure the *S* parameters.

1) Validation of DM Impedance Extraction: First, two known resistors (10 Ω and 1 kΩ) were chosen as the calibration impedances to measure the transmission *ABCD* matrix of the MF-LISN under DM noise source impedance measurement configuration.

Then, some π-mode networks were used as test objects. Each network was composed of an unknown resistor or an unknown *RLC* network as Z_d and two resistors of 1 kΩ as Z_{LG} and Z_{NG}. The value of Z_d in each network was different. The magnitude and the phase of different Z_d measured by the proposed method and an IA (Wayne Kerr 6500B) are shown in Fig. 8.

The relative errors of magnitude are less than 5% generally in the frequency range from 100 kHz to 30 MHz. The results of the phase are fairly accurate in most frequency points. We think the error may cause by the following possible reasons: 1) The phase below several megahertz is hard to be measured accurately and errors may occur. 2) The power grid may change with time. Meanwhile, the inductor(L_1) in LISN is not large enough to isolate the power grid in low frequency. 3) The MF-LISN we used is a prototype, and its layout and devices are not as good as a standard LISN. Thus, the error might increase.

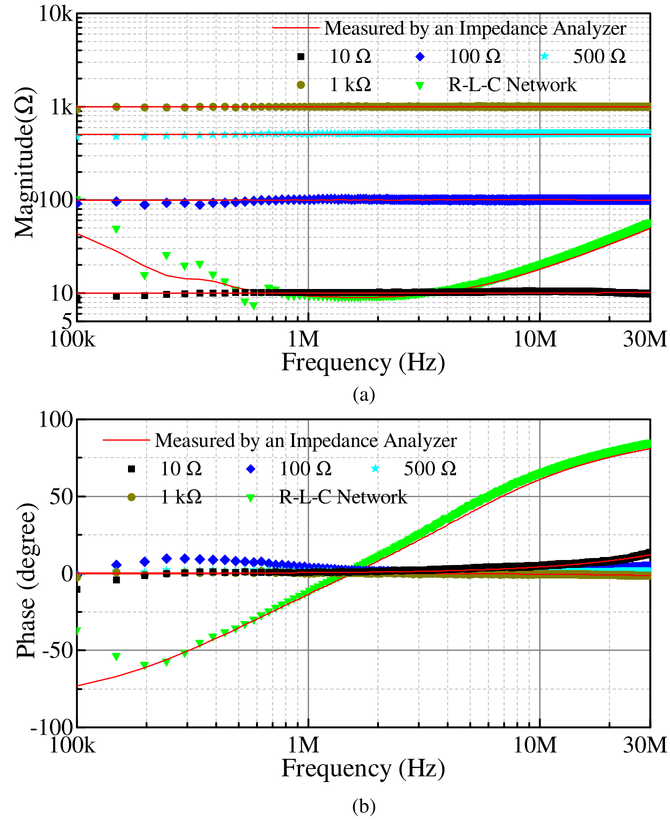


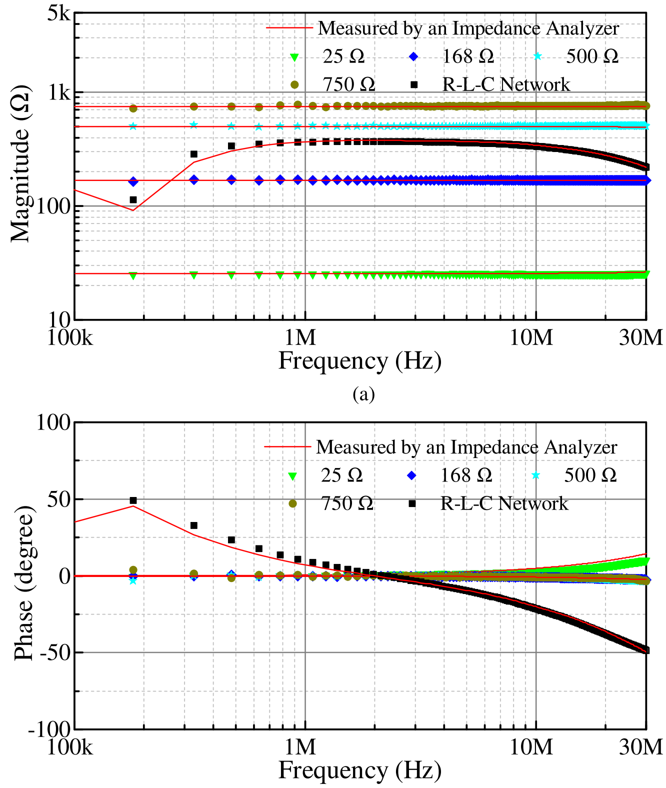
Fig. 8. Results measured by the proposed method and an IA. (a) Magnitude. (b) Phase.

2) Validation of CM Impedance Extraction: Two known resistors (10 Ω and 2.5 kΩ) were chosen as the calibration impedances. Then, some π-mode resistor networks were used as test objects. Each network was composed of a resistor of 10 Ω as Z_d and two unknown resistors or an unknown *LRC* network as Z_{LG} and Z_{NG}. The values of Z_{LG} and Z_{NG} in each network were different. The magnitude and the phase of different unknown Z_{LG} and Z_{NG} measured by proposed method and an IA (Wayne Kerr 6500B) are shown in Fig. 9.

The relative errors of magnitude were less than 5% in the frequency band from 100 kHz to 30 MHz. The results of the phase were fairly accurate in most frequency points. The uncertainty and the error of the results are caused by the similar reasons mentioned before.

B. Experimental Validation Using an SMPS

1) Noise Source Impedance Extraction: A commercial SMPS under normal operation condition was used to validate the proposed method. It is an isolated converter without EMI filter and the operating voltage is 24-V dc to 12-V dc. The Keysight E5071C VNA was used to measure the *S* parameters. The proposed method and MF-LISN were used to set up the measurement configuration, as shown in Figs. 2 and 5. The picture of practical measurement setup is shown in Fig. 10. In order to minimize the proximity effect, we kept the cables more than ten times from each other in this experiment, and the error caused by the proximity effect can be significantly reduced.



(a)

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Fig. 9. Results measured by proposed method and an IA. (a) Magnitude. (b) Phase.

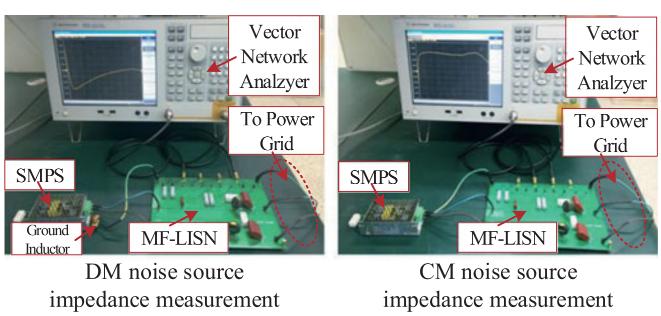
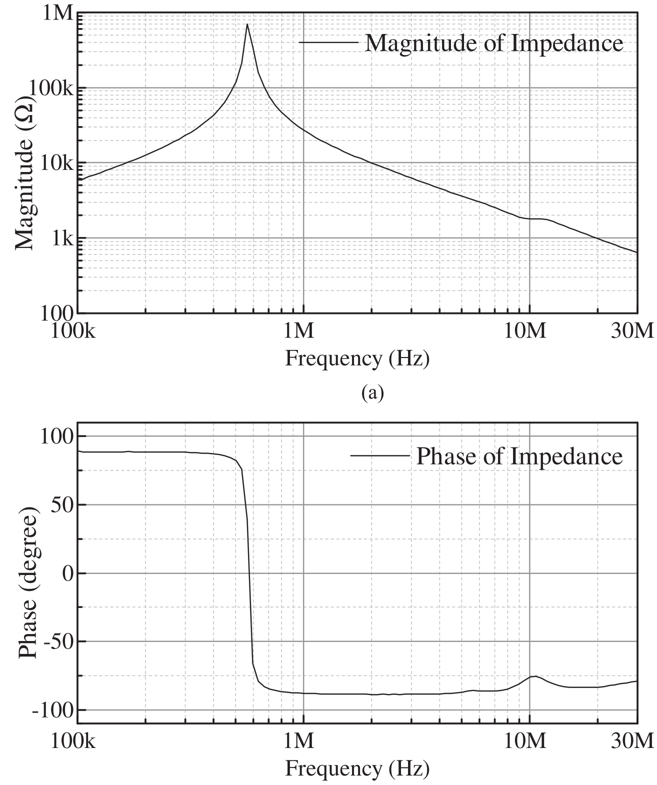


Fig. 10. Practical setup of experimental validation using an SMPS.

To measure the DM noise source impedance, as shown in Fig. 10, an inductor with a nominal value of 10 mH was connected between the ground of SMPS and the MF-LISN. The magnitude and the phase of the inductor we used are shown as Fig. 11.

Two known resistors (10 Ω and 1 kΩ) were also chosen as the calibration impedances first. Then, the magnitude and phase of DM noise source impedance of this SMPS can be measured as shown in Fig. 12 using the proposed method.

To measure the CM noise source impedance, two known resistors (10 Ω and 2.5 kΩ) were also chosen as the calibration impedances first. Then, the magnitude and phase of CM noise source impedance of this SMPS can be measured, as shown in Fig. 13.



(a)

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Fig. 11. Impedance of the ground inductor used in the experiment. (a) Magnitude. (b) Phase.

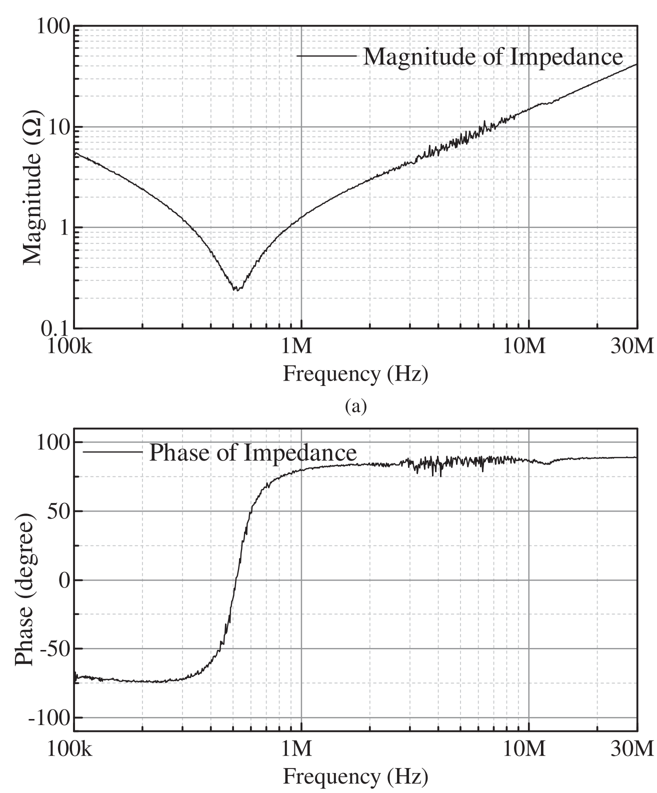

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Fig. 12. DM noise source impedance of an SMPS under operating conditions. (a) Magnitude. (b) Phase.

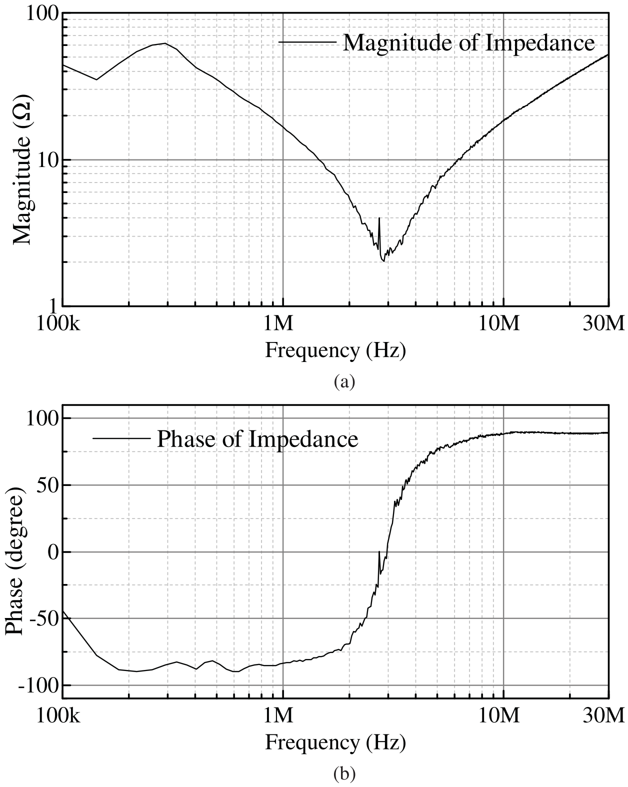

Fig. 13. CM noise source impedance of an SMPS under operating conditions. (a) Magnitude. (b) Phase.

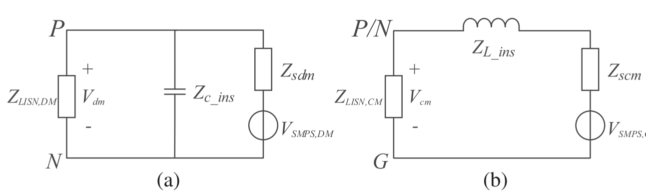

Fig. 14. Equivalent circuit of the EMI noise measurement when an filter circuit connected. (a) DM noise equivalent circuit. (b) CM noise equivalent circuit.

2) Validation of Extracted Noise Source Impedance of the SMPS: In order to validate the accuracy of the extracted noise source impedance of the SMPS, an experiment that is similar to [20] was designed. First, we used the MF-LISN, a CM/DM noise separator, and a spectrum analyzer to obtained the original DM noise $V_{\rm dm}$ and CM noise $V_{\rm cm}$. Then, an simple filter circuit with a known circuit was inserted between the SMPS and MF-LISN. In this situation, the DM and CM noise with filter can be easily predicted as $V_{\rm dm\_p}$ and $V_{\rm cm\_p}$ using the noise source impedance of SMPS, the impedance of the MF-LISN, and the parameters of filter. Finally, the actual DM and CM noise with filter can be measured as $V'_{\rm dm}$ and $V'_{\rm cm}$. When the measured noise matches the predicted noise, the extracted impedance of the SMPS is effective.

In practical, a DM capacitor with a nominal value of 100 μF for DM validation and a CM choke for CM validation were inserted, respectively. Fig. 14 shows the DM and CM noise measurement equivalent circuit using Thevenin's theorem [20], and the predicted DM noise and CM noise when the DM

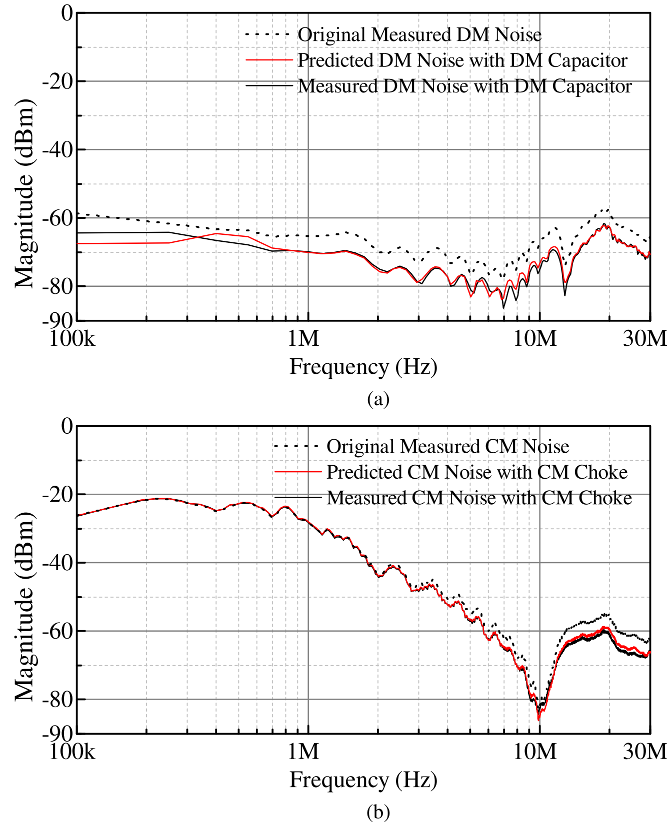

Fig. 15. Predicted and measured EMI noise. (a) DM noise. (b) CM noise.

capacitor or the CM choke was inserted can be expressed as

$$V_{\rm dm\_p}({\rm dB}) = V_{\rm dm}({\rm dB}) - 20\log\left|1 + \frac{Z_{\rm sdm}\, Z_{\rm LISN,DM}}{Z_{c\_\rm ins}(Z_{\rm sdm} + Z_{\rm LISN,DM})}\right| \quad (13a)$$

$$V_{\rm cm\_p}({\rm dB}) = V_{\rm cm}({\rm dB}) - 20\log\left|1 + \frac{Z_{L\_\rm ins}}{Z_{\rm scm} + Z_{\rm LISN,CM}}\right| \quad (13b)$$

where $V_{\rm dm}$ and $V_{\rm cm}$ are the original DM and CM noise, $Z_{\rm sdm}$ and $Z_{\rm scm}$ are the extracted DM and CM noise source impedance of the SMPS, $Z_{c\_\rm ins}$ is the impedance of the DM capacitor, $Z_{L\_\rm ins}$ is the impedance of the CM choke, $Z_{\rm LISN,DM}$ is the impedance of MF-LISN between the phase line and neutral line, and $Z_{\rm LISN,CM}$ is the impedance of MF-LISN between the ground and the terminal which is formed by shorting phase and neutral lines. $Z_{c\_\rm ins}$, $Z_{L\_\rm ins}$, $Z_{\rm LISN,CM}$, and $Z_{\rm LISN,DM}$ are measured by an IA (Wayne Kerr 6500B).

Meanwhile, when a DM capacitor or a CM choke was inserted, the actual DM noise and CM noise can be measured as $V'_{\rm dm}$ and $V'_{\rm cm}$. The predicted and measured EMI noise are shown in Fig. 15.

The error between the predicted and final measured noise is less than 2 dB in most frequency points (with less than 7% outliers for DM noise and less than 2% outliers for CM noise). Considering the uncertainty of measurement, the instrument error, and other factors, we believe that the result indicates that the accuracy of extracted impedance is good enough for EMI filter design.

IV. Conclusion

A noise source impedance extraction method under operating conditions is proposed in this letter. Since only two known resistors are used, the calibration can be implemented with power grid connected and the calibration procedure is considerably simplified. Using the proposed method, the current probes that may be unavailable are not required, and the injection effect in the low-frequency range is thus improved. We also demonstrated an MF-LISN with the function of EMI measurement and noise source impedance extraction, which make it convenient for the EMC pretest. The experiment results show that although the error in most frequency points are quite small, it is larger in the low-frequency range. Some further work needs to be done to solve this problem in the future.

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