Accuracy Improvement of Impedance Measurement for Nonlinear Devices

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***Abstract*—Impedance measurement for nonlinear devices is important in designing and tuning a system of wireless power transfer. Hence, this study has made preliminary contributions to the construction of an integrated real-time nonlinear impedance measurement system. Firstly, building upon previous work, this research deeply explores a nonlinear load impedance measurement method using only a directional coupler and an oscilloscope. Subsequently, addressing practical application scenarios, a calibration method based on the S-parameters of the directional coupler is proposed, further enhancing measurement accuracy. Finally, all data processing is encapsulated into a software, laying the foundation for future development of an integrated real-time measurement system.**

Keywords— nonlinear impedance measurement, directional couplers, oscilloscope, reflection coefficient, wireless power transfer

I. INTRODUCTION

As a novel energy supply pattern, Wireless Power Transfer (WPT) introduces a new way for energy acquisition, alleviating the excessive reliance on batteries in electric devices. Therefore, WPT is considered a highly promising technology [1].

For WPT, it is important to maximize power transfer efficiency. One key factor in achieving efficient power transfer is to design a impedance matching network to meet the condition of impedance matching. The primary task in designing a matching network is the accurate measurement of the load impedance in the WPT system.

In WPT, the load impedance exhibits nonlinear characteristics, because diodes and other semiconductor devices are included in the rectifier circuit. Therefore, wide range power level should be excited on the measured devices during the measurement. However, commonly used instruments, such as vector network analyzers (VNAs), can only provide power on the order of milliwatts and has to use additional component to prevent the direct current input. Therefore, how to accurately measure impedance of nonlinear devices becomes an critical issue.

To address these problems, many researchers have made remarkable contributions [2] [3] [4] [5]. These researches have provided us with valuable insights. However, they all face the drawback of complex operations. In practical applications, we want to establish a simpler, integrated, and real-time measurement system to achieve high-precision non-linear impedance measurement in WPT.

In order to realize this envisioned measurement system, in this paper, building upon our previous work [6], we firstly validate the proposed core measurement method, which can be accomplished solely with a directional coupler and an oscilloscope. Additionally, we take into account the characteristics of the couplers and proposed a method to improve measurement accuracy by using S-parameters, enabling high-precision measurements of the nonlinear devices. Finally, we also develop software for relevant data processing, laying the groundwork for the future construction of an integrated real-time measurement system.

The structure of this paper is as follows. In Chapter 2, the impedance measurement method is introduced. Chapter 3 presents a accuracy improvement method derived from the S-parameters of the directional coupler. Chapter 4 is the experimental validation, and Chapter 5 concludes the entire paper.

II. IMPEDANCE MEASUREMENT METHOD

The proposed impedance measurement method, using a directional coupler and an oscilloscope (noted as IMDCO in the following paper), is illustrated in Fig.1. A directional coupler is connected between the power source and the load, with the remaining two ports of the directional coupler (port 2 and port 3 as shown in Fig.1) connected to the oscilloscope. The core idea of the proposed IMDCO method is to measure the incident wave coupled from port 1 at port 2 and the reflected wave coupled from port 4 at port 3, calculate the reflection coefficient (Γ), and then derive the load impedance based on the Γ.

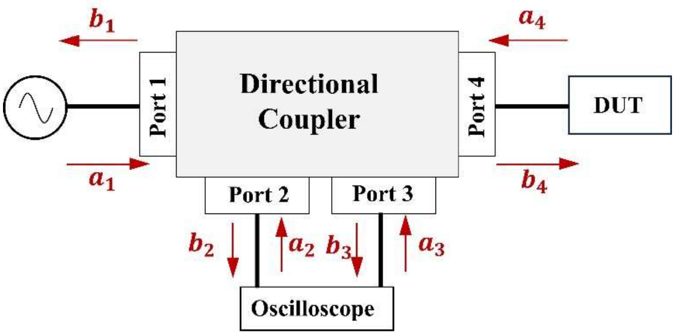

Figure 1：Shemctice of Proposed Impedance Measurement (IMDCO) Method

According to Fig.1, the Γ is defined as

$$\Gamma = \frac{a_4}{b_4} \tag{1}$$

where a_i and b_i represent the incident wave and the reflected wave at i^{th} port, $i = 1,2,3,4$.

Adjust the terminal impedance of the oscilloscope to 50Ω. Due to the presence of the directional coupler, assuming it is ideal, further obtaining the Γ as

$$\Gamma = \frac{a_4}{b_4} \approx \frac{b_3}{b_2} \tag{2}$$

Subsequently, the load impedance Z can be calculated according to the following formula.

$$Z = \frac{1+\Gamma}{1-\Gamma} Z_0 \tag{3}$$

where Z_0 is the characteristic impedance, here it is 50Ω.

III. Directional Coupler Calibration

The accurate measurement using the IMDCO proposed in Section II relies on the assumption that the directional coupler is ideal. For more common, non-ideal scenarios, this paper also propose a compensation method by measuring the S-parameters of the directional coupler to calibrate the above formulas, further enhancing the impedance measurement accuracy.

The VNA is first used to measure the S-parameters of the directional coupler at the operating frequency, and the relationship between the incident and reflected waves of the 4-port directional coupler is shown as follows

$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{pmatrix} \tag{4}$$

The Γ can be derived as

$$\Gamma = \frac{a_4}{b_4} = \frac{B_{32}S_{21} - S_{31}}{A - B_{32}B} \tag{5}$$

$$A = S_{41}S_{34} - S_{44}S_{31}$$

$$B = S_{41}S_{24} - S_{44}S_{21}$$

$$B_{32} = b_3/b_2$$

This calibration effectively improves the measurement accuracy of the proposed IMDCO method, while overcoming the limitations associated with the ideal directional coupler, demonstrating a more universal applicability. In the latter part of this paper, the measurement employing this compensation method will be denoted as I-IMDCO (Improvement on Impedance Measurement using Directional Coupler and Oscilloscope).

As another contribution of this paper, we have developed all the data processing involved in the measurement and use of compensation method into a software, to provide support for the future construction of an integrated measurement system. The Graphical User Interface (GUI) of the developed software is shown in Fig.2.

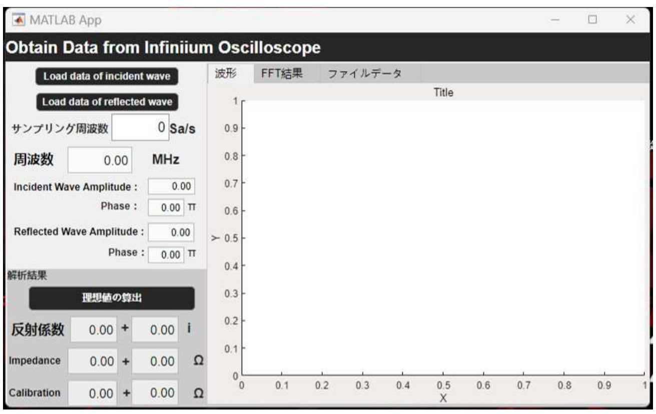

Figure 2: The GUI of the developed software

IV. Experimental Validation

To verify the accuracy of the proposed IMDCO method in Section II and the effectiveness of the I-IMDCO method in Section III, experimental validation has been conducted in this section. The experimental environment is illustrated in Fig.3, and the detailed information of the equipment used in the experiment is presented in Table 1.

Firstly, the impedance of the standard kit (50 Ω) was measured at 0 dBm and different frequency variations using a VNA as well as the IMDCO and I-IMDCO methods proposed in this paper, respectively, in order to validate the accuracy of the proposed methods. Subsequently, to confirm the advantages of the proposed method over VNA, the input impedance characteristics of a handmade rectifier was measured at 6.78MHz with higher input powers.

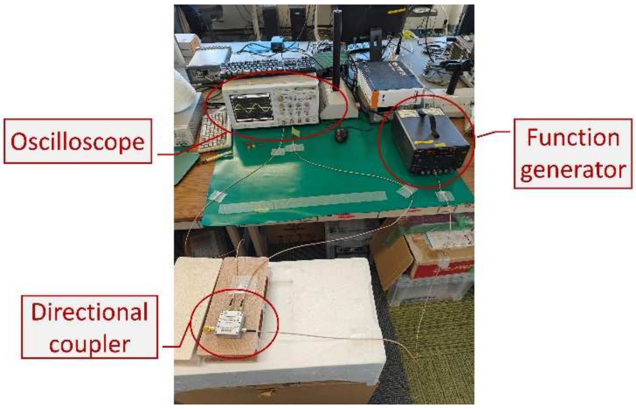

Figure 3: The Experiment Set-up

TABLE I. Equipment Information

Equipment	Model
Oscilloscope	Agilent Infiniium
Function Generator	Wave Factory WF1967
Directional coupler	Mini-Circuits ZFBDC-61HP+
VNA	Keysight E5071C

A. Standard kit verification

The IMDCO method proposed in Section II and the enhanced version, I-IMDCO, which incorporates S-parameter correction proposed in Section III have been used to make impedance measurements on 50Ω standard kits, respectively, and the results were compared with the data from the VNA in order to verify the accuracy of the measurement methods proposed in this paper. As the VNA is limited to milliwatt-level measurements, we standardized the input power to 0 dBm.

In Fig. 4, the time-domain waveforms of the incident and reflected waves coupled by the directional coupler, as measured by the oscilloscope, namely b2 and b3 as shown in Figure 1, are presented. Due to the standard 50 Ω load, the majority of the energy is efficiently transferred to the load, with only a small amount of energy reflected back, resulting in a significantly small magnitude of the reflected wave.

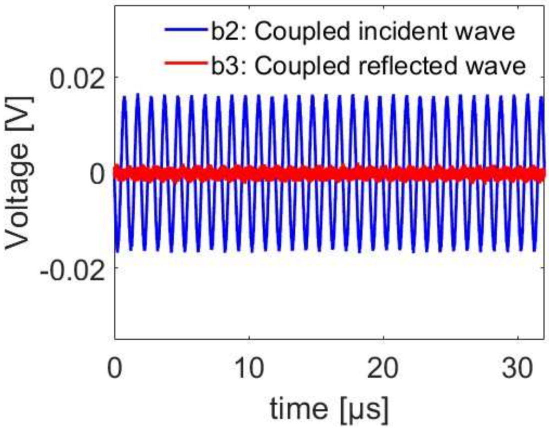

Figure 4: The incident and reflected waveform measured by oscilloscope (1MHz, 0 dBm)

Fig.5 illustrates the comparison of the measured load impedance. Additionally, it is worth noting that the design frequency range of the directional coupler is 1-60MHz. As evident from the results in Fig. 5, within the coupler's designed frequency range, both methods align well with the results from the VNA. However, beyond 60MHz, where the coupler cannot effectively distinguish between incident and reflected waves, the IMDCO method exhibits significant deviations. Contrastingly, the I-IMDCO method with S-param improvement noticeably enhances precision, accurately determining the load impedance.

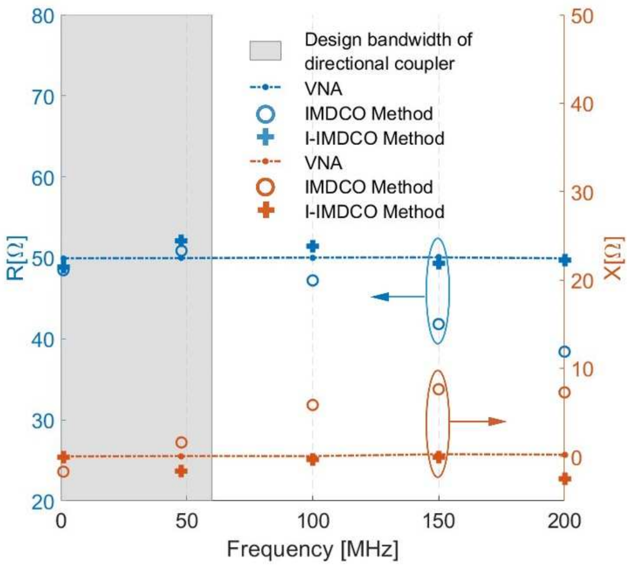

Figure 5: Comparison of measurement results for the 50Ω standard kit.

B. *Handmade rectifier impedance versus input power*

Because the proposed measurement method is designed for higher input powers compared to VNA, to demonstrate its effectiveness under such conditions, we prepared a handmade rectifier, which is shown in Fig.6.

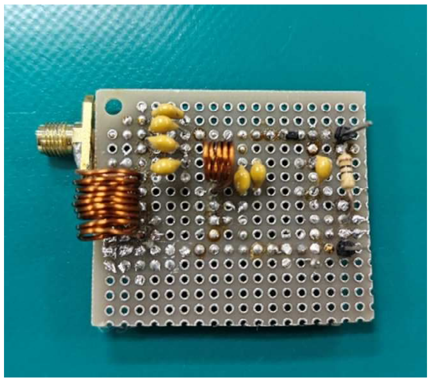

Figure 6: The handmade rectifier

Then, we employed the proposed method to measure the variation of input impedance of the rectifier at 6.78 MHz under power inputs ranging from 0 to 1W. From the time-domain waveform shown in Fig. 7, it can be observed that compared to the 50 Ω load condition in Fig. 4, the handmade rectifier exhibits stronger reflections. The measured impedance is illustrated in Figure 8. The logarithmic scale is used for the x-axis values. From the comparison of the measurement results, at the measurement frequency of 6.78MHz, the directional coupler approaches its ideal state, so the measurement results of both IMDCO and I-IMDCO are very similar. At the same time, the measurement results distinctly reveal the nonlinearity of the rectifier. This indicates that our proposed method, no matter IMDCO or I-IMDCO is applicable across various input power scenarios, offering advantages that cannot be replaced by devices such as VNA.

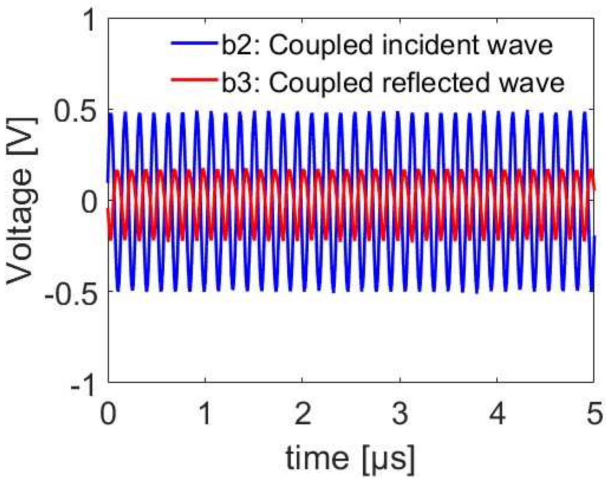

Figure 7: The incident and reflected waveform measured by oscilloscope (6.78MHz, 30dBm)

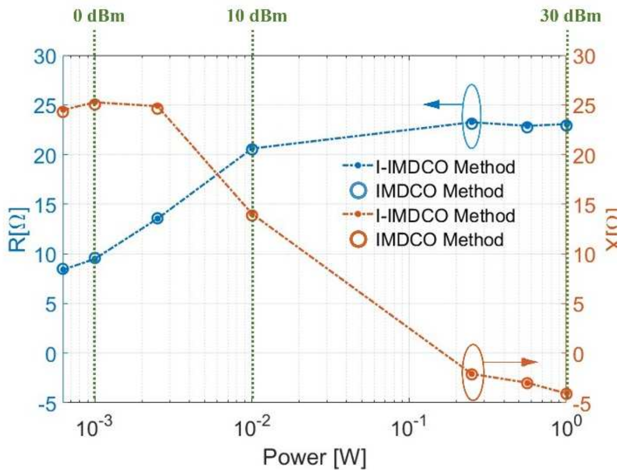

Figure 8: Input Impedance of the rectifier versus input power

V. CONCLUSION

In this study, for the purpose of constructing an integrated real-time nonlinear impedance measurement system, we conducted preliminary explorations.

Firstly, we validated the effectiveness of the proposed measurement method, demonstrating that nonlinear load impedance measurements with various input powers can be achieved solely using a directional coupler and an oscilloscope. The operation is straightforward and the measurement results are accurate.

Secondly, we developed a calibration method that significantly improves measurement accuracy, even when the coupler is in a non-ideal state during practical applications.

Finally, all data processing was encapsulated into software, laying the groundwork for the future construction of an integrated real-time non-linear impedance measurement system.

As a preliminary research, we conducted tests with a maximum power of 1W. However, we believe that the proposed nonlinear impedance measurement method and the accuracy improvement method hold the potential for successful application in higher power conditions (more than 1W). This is also one of the important directions for our future research.

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