IMTC 2005 - Instrumentation and Measurement
Technology Conference
Ottawa, Ontario, Canada, May 17–19, 2005

The Load Impedance Measurement in the Time-Frequency Domain Reflectometry System

TokSon Choe[1], Ki-Seok Kwak[1], Yong-June Shin[2], Jin Bae Park[1], Tae Sung Yoon[3]

[1]Department of Electrical and Electronic Engineering, Yonsei University,
Control Engineering Lab, Room C609, Seoul 120-749, Korea
Phone: +82 2 2123 2773, Fax: +82 2 362 4539, E–mail: tschoe@control.yonsei.ac.kr.

[2]Department of Electrical Engineering, The University of South Carolina,
301 S.Main Street, Swearingen, Room 3A20 Columbia, SC 29208, U.S.A
Phone: +1 803 777 9569, Fax: +1 803 777 8045, E–mail: shinjune@engr.sc.edu.

[3]Department of Electrical Engineering, Changwon National University,
Room A219, Sarim-dong, Changwon, Kyungnam, 641-773, Korea
Phone: +82 55 279 7513, Fax: +82 55 263 9956, E–mail: tsyoon@sarim.changwon.ac.kr.

Abstract – *In this paper, a new signal processing based methodology is suggested in order to measure the load impedance with high accuracy and resolution. This methodology is characterized by a chirp signal with Gaussian envelope which enables one to achieve time localization and to assign energy in the frequency band of interest. A normalized time-frequency cross correlation function is utilized to evaluate the reflection coefficient, and a cross time-frequency distribution function is used to acquire the phase difference between the input and the reflected signals. In this paper, the real experiments are achieved on a coaxial cable which is the typical transmission line in the electrical wiring system by using the time-frequency domain reflectometry (TFDR) system and terminal resistors to verify the performance of the suggested methodology. The experimental results of the TFDR based impedance measurement are compared with those of the commercial time domain reflectometry (TDR) system.*

Keywords – *Time-Frequency Domain Reflectometry, Load Impedance, Normalized Time-Frequency Cross Correlation Function, Cross Time-Frequency Distribution Function.*

I. INTRODUCTION

The state-of-the-art TDR systems in commercial instrumentation and measurement engineering are oriented to the application to the high speed electrical circuits, which are designed to operate in the typical characteristic impedance. However, the accuracy of impedance measurement in the TDR based measurement is limited within the close neighborhood of the characteristic impedance only. Nevertheless, an accurate measurement of impedance in wide range of load impedance is required for the applications to the contemporary high-speed and high performance circuits [1].

In order to enhance accuracy and resolution in the classical TDR or frequency domain reflectometry (FDR), TFDR methodology has been proposed for the detection and localization of the wiring integrity [3]. As an extension of TFDR application, a new evaluation methodology of the load impedance based on the TFDR [2] was suggested in order to resolve the accuracy limitations in classical reflectometry. The TFDR systems is characterized by a chirp signal with Gaussian envelope which enables one to achieve time localization and to assign energy in the frequency band of interest, a normalized time-frequency cross correlation function to evaluate the magnitude of reflection coefficient, and a cross time-frequency distribution function to acquire the phase difference between the incident and the reflected signals.

This paper is organized as follows: In Section II, an evaluation methodology of the load impedance is discussed. The discussion in Section II will be focused on the measurement of complex reflection coefficients by use of the normalized time-frequency cross correlation function and the cross time-frequency distribution function. In Section III, the real-world experiments are achieved on a coaxial cable which is the typical transmission line in the electrical wiring system in order to verify the feasibility and accuracy of the proposed methodology. The experimental results of the TFDR based impedance measurement are compared with those of the commercial TDR system. The conclusion of this paper is given in Section IV.

II. EVALUATION OF THE LOAD IMPEDANCE

In order to evaluate the load impedance (Z_L) of the transmission line with reflectometry, it is necessary to determine the characteristic impedance (Z_0) and the reflection coefficient (Γ). The load impedance is defined as follows [7]:

$$Z_L = \frac{1+\Gamma}{1-\Gamma} Z_0 = \frac{1+|\Gamma|e^{j\theta}}{1-|\Gamma|e^{j\theta}} Z_0 \qquad (1)$$

As shown in equation (1), the measurement of the load impedance requires estimations of the magnitude and phase difference between the input and the reflected signals.

In TDR, a step pulse signal is used for an input signal, whereas the reflected signal arising at the impedance mismatched point in cable is analyzed to evaluate impedance by comparing the energy ratio between input and reflected signals [1]. The edge of the TDR input signal has a tendency to be smeared owing to the frequency-dependent attenuation of the transmission line so that one cannot obtain precise energy ratio between the input and the reflected signals. Also, complex impedance can not be measured via TDR, only the state of "open" or "short" is determined.

However, in the TFDR, the input signal is designed as a time localized chirp signal whose frequency band is selected by the attenuation characteristics of the cables [3]. Hence, the time-frequency characteristics of the input and reflected signals are utilized in order to estimate the complex load impedance. For the evaluation of the reflection coefficient in the TFDR, the energy ratio and the phase difference between the input and the reflected signals are required.

A. Calculation of Magnitude

The magnitude of the complex reflection coefficient can be evaluated by the energy ratio. In the TFDR, the energy ratio of the reflected signal to the input signal can be obtained by the normalized time-frequency cross correlation function between the input and the reflected signals. The normalized time-frequency cross correlation function [3] is defined as follows:

$$C_{sr}(t) = \frac{2\pi}{E_s E_r(t)} \int_{t'=t-T_s}^{t'=t+T_s} \int W_r(t',\omega) W_s(t'-t,\omega) d\omega dt' \quad (2)$$

where the T_s is the time duration of the TFDR input signal, the $W_s(t,\omega)$ is the Wigner distribution of the reference signal $s(t)$, and $W_r(t,\omega)$ is the Wigner distribution of the reflected signal $r(t)$. The denominators E_s and $E_r(t)$ are defined for the normalization of the time-frequency cross correlation function as follows:

$$E_r(t) = \int_{t'=t-T_s}^{t'=t+T_s} \int W_r(t',\omega) d\omega dt' \quad (3)$$

$$E_s = \int\int W_s(t,\omega) dt d\omega \quad (4)$$

If the frequency-dependent attenuation characteristics of the cable (A_f) is available, which is typically provided by the manufacturer of the cable, the absolute value of the reflection coefficient(Γ) is calculated as follows:

$$|\Gamma| = \frac{1}{A_f}\sqrt{\frac{E_r}{E_s}} \quad (5)$$

B. Calculation of Phase

The another factor of the complex impedance, i.e., the phase difference θ is also evaluated by the accurate localization of the input and the reflected signals. The phase difference θ is obtained by using the cross time-frequency distribution function

Fig. 1. Terminal resistors

between the reference and the localized reflected signals. The cross time-frequency distribution function [6] is defined as follows:

$$J_{sr}(t,\omega;\phi) = \frac{1}{4\pi^2}\int\int\int s(u+\frac{\tau}{2}) r^*(u-\frac{\tau}{2}) \phi(\theta,\tau) \times e^{-j\theta t - j\tau\omega + j\theta u} d\theta d\tau du \quad (6)$$

$$J_{sr}(t,\omega;\phi) = |J_{sr}(t,\omega;\phi)| e^{j\Theta_{sr}(t,\omega;\phi)} \quad (7)$$

$$\Theta_{sr}(t,\omega;\phi) = tan^{-1}[\frac{Im(J_{sr}(t,\omega;\phi))}{Re(J_{sr}(t,\omega;\phi))}] \quad (8)$$

where $\Theta_{sr}(t,\omega;\phi)$ is the time-frequency phase information between the reference signal $s(t)$ and the localized reflected signal $r(t)$.

The time-frequency localized phase difference θ is obtained by the substitution of center time (t_{sr}), average value for each time center of the reference and the localized reflected signals, and center frequency (ω_{sr}), average value for each frequency center of the reference and the localized reflected signals, in equation (8).

$$\theta = \Theta_{sr}(t_{sr},\omega_{sr};\phi) \quad (9)$$

Hence, the complex reflection coefficient Γ can be calculated by equation (1) with knowledge of the evaluated magnitude of reflection coefficient $|\Gamma|$ and a phase difference θ.

III. EXPERIMENTAL SETUP AND RESULTS

To demonstrate the feasibility of the suggested methodology for the measurement of the load impedance in a coaxial cable, a set of experiments is achieved with terminal resistors, the TFDR system [4] and the TDR instrument.

Fig. 1 shows terminal resistors. In Fig. 1, the left one exhibits the terminal resistor itself, and the right one indicates the connection with the target cable. Generally, a terminal resistor is used for absorption of the transmission signal in the end of the cable to get rid of reflection. The load impedance is implemented through using of these terminal resistors which have the arbitrary values(10, 20, 30, 40, 50, 60, 70Ω) with an error of less than 10 percent.

To verify the suggested methodology, we employed the TFDR system. The employed TFDR system is shown in Fig. 2

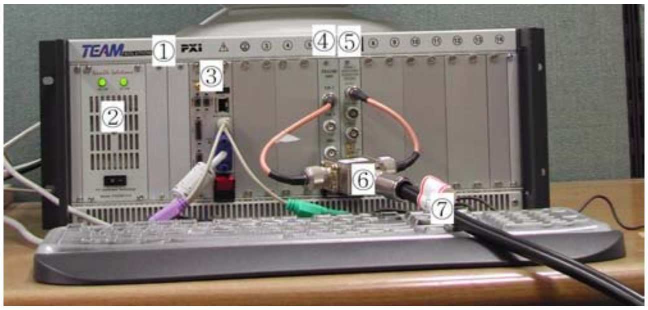

Fig. 2. The TFDR System

and composed of PXI instruments (① PXI Chassis, ② Power Supply, ③ PXI Embedded Controller, ④ $100MS/s$ Digital Storage Oscilloscope(DSO), ⑤ $100MS/s$ Arbitrary Waveform Generator(AWG), ⑥ Circulator, and ⑦ Target cable).

To compare the accuracy of the suggested methodology, we use a commercial TDR instrument. In these experiments, 10C-FBT is selected as a target cable, which is typically used for the image data transmission between a broadcasting station and subscribers. The $100[m]$ length of the target cable is decided after considering the blind spot of the used TFDR system.

In the real experiments, the reference signal which has time duration 700[ns] and frequency bandwidth 10-20MHz is used. Even though the frequency attenuation property per unit length of the target cable is provided by the manufacturer, the measured value for the center frequency of the reference signal is applied for accurate experiment. Because the frequency attenuation property for the interest frequency is not provided. The real measured value (A_f) for the 15MHz is $5.0376 \times 10^{-1}/100[m]$.

Fig. 3 exhibits the experimental results for $100m$ target cable with terminal resistor 10Ω. Fig. 3-(a) is the acquired signal from DSO in the TFDR system when the load impedance is 10Ω. In the TFDR system, the AWG module generates the designed signal. It is transmitted to a circulator. The first waveform from the left side in the Fig. 3-(a) is the input signal. The input signal is reflected from the terminal resistor at the end of the cable and acquired in the DSO via the circulator. It represents the second waveform from the left side in the Fig. 3-(a). Fig. 3-(b) shows the normalized time-frequency cross correlation between the reference signal $s(t)$ and the reflected signal $r(t)$.

In the real experiment, the detailed procedure for acquiring of the reference signal $s(t)$ can be described as follows: The first, the time center of the first waveform from the left side in the Fig. 3-(a) is selected approximately by sight. The second, approximated reference signal is obtained by extracting the first waveform with wider time duration than T_s around that time center, and the exact time center of the reference signal is calculated by taking a mean of the approximated reference signal in the time axis. Finally, the exact reference signal is obtained by extracting this approximated signal with time

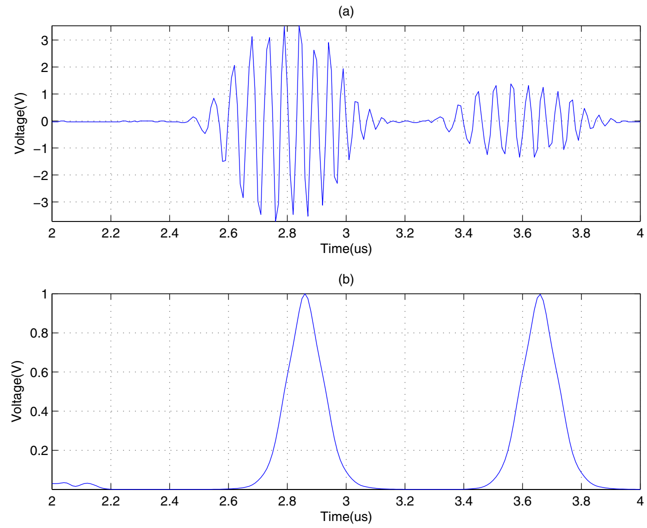

Fig. 3. TFDR waveform in (a) and corresponding normalized time-frequency cross correlation function in (b) with load impedance $Z_L = 10\Omega$

duration T_s around the renewed time center.

The localized reflected signal $r'(t)$ can be obtained by the normalized time-frequency cross correlation between the reference and the reflected signals. The localized reflected signal $r'(t)$ is calculated by extracting the second waveform in the Fig. 3-(a) with time duration T_s around the second peak time of Fig. 3-(b). When the terminal resistor connected with the cable is 10Ω, the calculated energy of the reference signal, E_s and that of the localized reflected signal ,E_r are 4.6447×10^5 and 6.5462×10^4, respectively. The reflection coefficient Γ can be calculated by putting known A_f, E_s, and E_r to equation (5) as shown in equation (10).

$$|\Gamma| = \frac{1}{5.0376 \times 10^{-1}} \times \sqrt{\frac{6.5462 \times 10^4}{4.6447 \times 10^5}} = 0.7452 \quad (10)$$

The phase difference between the reference and the localized reflected signals can be calculated by the cross time-frequency distribution function. The cross time-frequency distribution between the reference and the reflected signals is obtained by substituting the reference signal $s(t)$ and the localized reflected signal $r'(t)$ in the equation (6). The time-frequency phase information $\theta(t, w; \phi)$ between the reference and the localized reflected signals by placing the result of equation (6) to equation (8). To evaluate the phase difference between the reference and the reflected signals, we must know the t_{sr} and ω_{sr}. The t_{sr} and the ω_{sr} are calculated by following procedures. The Wigner distributions $(W_s(t,\omega))$, $W_{r'}(t,\omega)$ of the reference signal $(s(t))$ and the localized reflected signal $(r'(t))$ have to be calculated. The second, mean time t_{sr} and mean frequency ω_{sr} are obtained by taking average of each time center and frequency center index in the Wigner distributions ($W_s(t,\omega)$ and $W_{r'}(t,\omega)$).

When the terminal resistor is 10Ω, the phase spectrum for

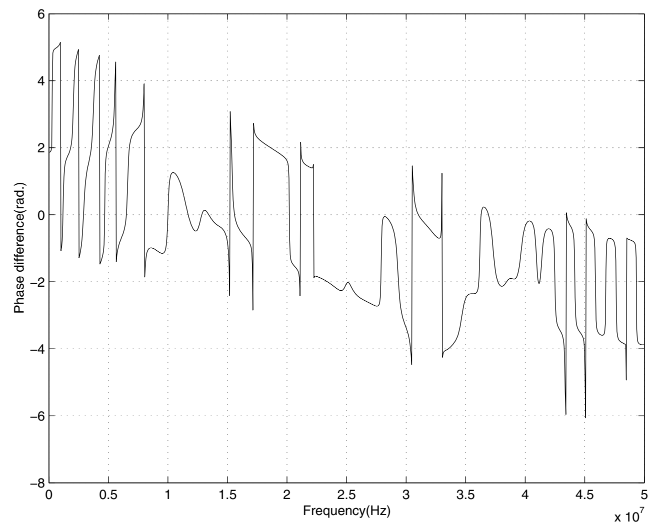

Fig. 4. The phase spectrum for TFDR with load impedance $Z_L = 10\Omega$

t_{sr} is depicted in Fig.4. In case frequency is ω_{sr} the acquired phase value implies the phase discrepancy between the input and the reflected signals. When the terminal resistor is 10Ω the phase difference θ is obtained as $2.0065[rad]$.

In Table I, the experimental results are provided for the different values of the load impedance by using the TFDR and TDR under the same experimental conditions. The measurement error based on the TDR is accurate in the neighborhood of the characteristic impedance, however, the accuracy degrades as the value of the load impedance decreases. However, the measurements of the load impedance via the TFDR based methodology show smaller error than the TDR based methodology. This limitation of the accuracy is an inherent problem of the TDR reference signal where the dc step pulse contains a wide (theoretically infinite) frequency bandwidth. The attenuation of the high-frequency components results in a rounded reflected pulse. However, in the TFDR, the instantaneous energy is allocated in narrower frequency bandwidths so that the distortion of the incident waveform is reduced. In addition, the inevitable distortion by the frequency-dependent attenuation is compensated by the estimation of the frequency offset of the reflected waveform. Therefore, higher accuracy of impedance measurement can be achieved via TFDR over a wider frequency range.

IV. CONCLUSIONS

In this paper, TFDR-based impedance measurement methodology proposed in [2] is implemented. TFDR allows one to compensate the error of impedance measurement caused by distortion in transmission line by measuring phase difference and local frequency offset between the input and the reflected signals. The implemented experimental system is composed of the TFDR as a main framework and terminal resistor as load impedance. The experimental results imply

TABLE I
EXPERIMENTAL RESULTS OF TFDR AND TDR

	TFDR				TDR
$Z_L[\Omega]$	$\tilde{D}[m]$	$\tilde{\theta}_{sr}[rad]$	$\lvert\tilde{\Gamma}\rvert$	$\tilde{Z}_L[\Omega]$	$\tilde{Z}_L[\Omega]$
10	99.9940	2.0065	0.7452	10.5105	16.906
20	100.0083	2.0259	0.5515	20.8118	25.813
30	99.9542	2.0057	0.3938	31.3136	34.906
40	99.8740	2.0032	0.2708	41.3101	44.000
50	99.7227	1.9775	0.1626	51.8553	53.375
60	99.5590	1.9424	0.0702	62.5604	62.906
70	100.7405	0.0696	0.0229	68.7704	72.406

that it is possible to acquire more accurate complex impedance with comparatively lower performance instruments than those of the conventional commercial TDR.

V. ACKNOWLEDGEMENT

This research is supported by the United States Office of Naval Research (ONR) grants, N00014-02-1-0623. Also this research is partially supported by NASA EPSCoR Research Grant Program, 20030194TO0034.

VI. REFERENCES

[1] N. G. Paulter, "An Assessment on the Accuracy of Time-Domain Reflectometry for Measuring the Characteristic Impedance of Transmission Line," *IEEE Transactions on Instrumentation and Measurement,* Vol. 50, No. 5, p. 1381-1388, Oct. 2001.

[2] YongJune Shin, Edward J. Powers, TokSon Choe, SeungHoon Sung, JongGwan Yook, JinBae Park, "Evaluation of the Load Impedance in Coaxial Cable via Time-Frequency Domain Reflectometry," *Advanced Signal Processing Algorithms, Archtectures, and Implementations XIII, Proceedings of SPIE*, Vol. 5205, p. 38-46, Dec. 2003.

[3] TokSon Choe, ChanYoung Hong, EunSeok Song, JongGwan Yook, JinBae Park, YongJune Shin, Edward J. Powers, "Detection and Estimation of a Fault on Coaxial Cable via Time-Frequency Domain Reflectometry," *Proceedings of the 20th IEEE Instrumentation and Measurement Technology Conference*, Vol. 1, p. 190-195, 20-22 May 2003.

[4] TokSon Choe, ChanYoung Hong, JinBae Park, TaeSung Yoon, "Implementation of Time-Frequency Domain Reflectometry System with PXI Platform for a Coaxial Cable," *Proceedings of the 21th IEEE Instrumentation and Measurement Technology Conference*, Vol. 2, p. 964-968, 18-20 May 2004.

[5] Agilent Technology Impedance Measurement Handbook, 2nd Edtion, 2002, Agilent Technologies Co. Ltd.

[6] YongJune Shin, Edward J. Powers, William M. Grady, S. C. Bhatt, "Cross Time-Frequency Distribution Function," *Advanced Signal Processing Algorithms, Archtectures, and Implementations X, Proceedings of SPIE*, Vol. 4116, p. 9-16, Nov. 2000.

[7] David M. Pozar, "Microwave Engineering," John Wiley & Sons, Inc. 1998.