A Broadband S/SSTDR-VNA for Energized Circuits

Evan Benoit,
Department of Electrical and Computer Engineering
University of Utah
Salt Lake City, UT, USA
evan.benoit@utah.edu

Cynthia Furse,
Department of Electrical and Computer Engineering
University of Utah
Salt Lake City, UT, USA
cynthia.furse@utah.edu

***Abstract*—We propose the use of the Spectral Time Domain Reflectometry (STDR) and Spread Spectrum Time Domain Reflectometry (SSTDR) methods as a substitute for a vector network analyzer (VNA) to extract complex impedance and S-parameters. S/SSTDR can be used on energized systems, opening up opportunities for new test capabilities of real time measurements on functioning systems from near-DC through higher frequencies. This test modality also opens up the opportunity to test multiple channels simultaneously by using multiple uncorrelated PN codes. This could prove useful in applications such as medical imaging (MRI or microwave imaging), where scans between many antennas are combined to create the image.**

I. Introduction

Vector network analyzers (VNA) are currently the most widely used tool for of characterizing the high frequency characteristics of electrical circuits/components. A VNA sends a set of sinusoidal signals into the device under test and measures the magnitude and phase (S-parameters) of the reflected and transmitted signals from/through the device [1]. However, due to the sensitivity of the equipment used to construct a VNA, they are not suited for use on energized systems without specialized protection equipment.

We propose a method of S-parameter measurement for energized systems using Spectral Time Domain Reflectometry (STDR) and Spread Spectrum Time Domain Reflectometry (SSTDR). Both of these methods are currently being used to detect nad locate faults on energized electrical systems.

II. S/SSTDR Overview

A. Reflectometry principles

Reflectometry methods launch a test signal into a transmission line (TL), where it travels down the TL until an impedance discontinuity is reached, at which point some or all of the incident signal is reflected back toward the source [2]. The reflected signal is captured and compared to the incident signal to extract information about the impedance discontinuity, described by the reflection coefficient (Γ)

$$\Gamma_L(\omega) = \frac{Z_L(\omega) - Z_0}{Z_L(\omega) + Z_0}, \quad (1)$$

where (Z_0) is the TL characteristic impedance, (Z_L) is the impedance of the discontinuity, and ω denotes any frequency dependence of the impedance discontinuity/load. The reflection coefficient acts on the incident signal to produce the reflected signal,

$$ReflectedSignal(\omega) = IncidentSignal(\omega) \cdot \Gamma_L(\omega). \quad (2)$$

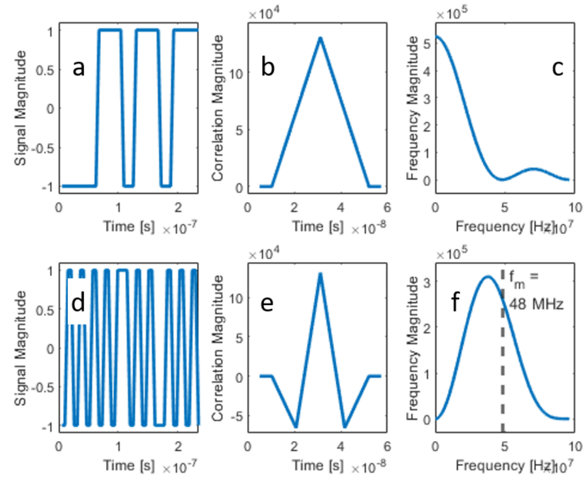

Fig. 1. a: PN code/STDR incident signal. b: STDR pulse from correlated STDR signal. c: Positive frequency domain data of correlated STDR pulse. d: Square wave modulated PN code/SSTDR incident signal. e: SSTDR pulse from correlated SSTDR signal. f: Positive frequency domain data of correlated SSTDR pulse, with dotted line marking the modulation frequency.

B. S/SSTDR signal construction and analysis

The incident signal for both STDR and SSTDR begins with a pseudorandom noise (PN) code created by a linear feedback shift register (LFSR). The length of the PN code is determined by the total number of registers in the LFSR. A square wave modulation is used in the SSTDR simulation. Figure 1a shows a portion of the incident PN code, which is also the STDR signal. Figure 1d depicts the incident SSTDR signal which is the result of modulating the PN code with a square wave of a desired modulation frequency (f_m).

As with standard reflectometry methods, the STDR or SSTDR incident signal is sent down a transmission line (TL) where an impedance discontinuity causes a reflection of the signal that follows (1). The reflected signal (2) returns to the reflectometry device where it is captured and correlated with a copy of the incident signal. Figure 1b is the correlated STDR

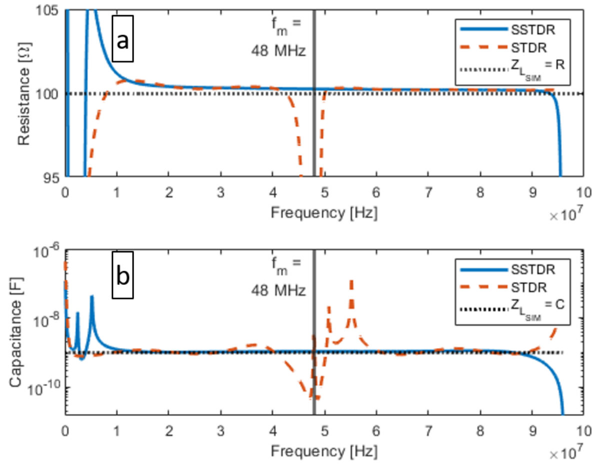

Fig. 2. Sample of impedance extraction as a function of frequency using only the incident and reflected signals as well as the characteristic impedance of the TL. a: Resistance. b: Capacitance

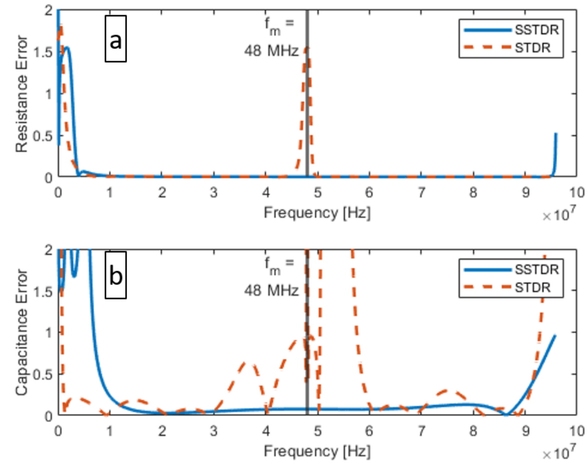

Fig. 3. Error in extracted ZL across the entire bandwidth in the S/SSTDR signals. a: Resistance. b: Capacitance

signal and Figure 1e is the correlated SSTDR signal. Magnitude and frequency dependence of the impedance discontinuity is captured within the reflected signal and can be seen in the amplitude and shape of the correlated time-domain signal, respectively.

To analyze the frequency dependence of the impedance discontinuity as a function of frequency (ω), we convert the correlated signal from the time domain to the frequency domain by use of the Fourier transform. In the frequency domain, the STDR bandwidth is centered around zero, and the lower frequencies possess the highest amplitude (Figure 1c). The SSTDR bandwidth is centered near the modulation frequency (Figure 1f). Additional calculations to extract frequency dependent information about the impedance mismatch can be accomplished while in the frequency domain.

C. Extracting Complex Impedance with S/SSTDR incident and reflected signals

Since the incident signal is modified by the reflection coefficient to produce the reflected signal, shown by (2); it remains possible to extract the reflection coefficient using a copy of the incident and reflected signals, as in, $\Gamma_{L_{EXT}}(\omega) = \frac{ReflectedSignal(\omega)}{IncidentSignal(\omega)}$. This relationship then allows us to extract the complex impedance $(Z_{L_{EXT}})$ by rearranging (1) and substituting $\Gamma_{L_{EXT}}$ in for the theoretical Γ_L.

To test this concept, a complex load was simulated using a resistance of 100 Ω and a capacitance of 1 nF to produce reflected S/SSTDR signals. The results of extracting the load impedance as a function of frequency are shown in Figure 2, where the dotted line shows the simulated values $(Z_{L_{SIM}}(\omega))$ as reference.

D. Analyzing the Accuracy of the Extracted Impedance

We chose to use a calculation of error to measure the agreement/disagreement between the simulated load $Z_{L_{SIM}}(\omega)$ and the extract load $Z_{L_{EXT}}(\omega)$. Figure 3 shows this error across the entire bandwidth of the STDR and SSTDR signals. It is important to note that the error in the extracted impedance is the lowest where the magnitude of the S/SSTDR signals are highest. This means, we can use a portion of the frequency domain information from the STDR measurement and combine it with the frequency domain information from the SSTDR measurement to determine the frequency response of a load beginning at DC and ending at a higher frequency.

III. Conclusion and Future Work

We have found that the S/SSTDR method can be used to extract complex impedance and reflection coefficient. Transmission coefficients could similarly be extracted if signals were transmitted between two S/SSTDR sensors. Because S/SSTDR can be used on energized systems without interference, this opens up opportunities for new test capabilities of real time measurements on functioning systems. In addition, this approach has the ability to improve sensitivity and signal to noise ratio (SNR) by averaging, baselining and signal processing, and using longer PN codes, etc. Bandwidth can be expanded from near-DC (using STDR) through higher frequencies using one or more SSTDR signals. This test modality also opens up the opportunity to test multiple channels simultaneously by using multiple uncorrelated PN codes. This could prove useful in applications such as medical imaging (MRI or microwave imaging), where scans between many antennas are combined to create the image.

References

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[2] C. Furse, Y. C. Chung, C. Lo, and P. Pendayala, "A critical comparison of reflectometry methods for location of wiring faults," *Smart Structures and Systems*, vol. 2, no. 1, pp. 25–46, 2006.