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CHAOS TIME-DOMAIN REFLECTOMETRY FOR FAULT LOCATION ON LIVE WIRES*

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Abstract We propose a chaos time-domain reflectometry (CTDR) for locating faults on live wires. This method uses a chaotic output of an improved Colpitts oscillator as probe signal, and detects wire faults by correlating a duplicate with the echo of the probe signal. Benefiting from the anti-jamming of the correlation function of the wideband chaos, fault location on live wires can be achieved. We experimentally demonstrate the detection for live wires in a digital communication system, in which a type of digital signal named high density bipolar of order 3 (HDB3) is transmitted. The effects of the chaotic probe signal on the bit error rate (BER) of the transmitted HDB3 at different rates are analyzed. Meanwhile, the influences of the backward HDB3 reflected by wiring faults on the signal-noise-ratio (SNR) of CTDR measurement are examined experimentally. The results show that fault detection on live wires is achieved when the power of the chaotic probe signal is about from -24.8 dB to -13.5 dB lower than that of the transmitted digital signal. In this case, the BER is kept less than 3E-10, and the SNR of CTDR is higher than 3 dB. Besides, the auto-correlation properties of the improved Colpitts oscillator at different states are investigated experimentally to explore the suitable chaotic states for the CTDR.

Keywords Chaotic signal, high density bipolar of order 3, fault location, live wire.

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1. Introduction

Maintenance of aging wiring is a great challenge, especially for space shuttle, warship, large industrial machinery, and other densely wired systems (NASA [5], NSTC [6], Furse & Haupt [1]). Detection of faults on live wires is of much concern because the health of wires especially aging wires must be monitored without disturbing or suspending services of electrical systems. Hence, detection method is required to keep the tested wires being alive and on work, meanwhile the probe signal must have little effect on the transmitted signals on wires (Smith et al. [8]).

Currently, several methods for locating faults on live wires have been developed (Furse et al. [2]). The major methods include sequence time-domain reflectometry

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(STDR) (Sharma et al. [7]), spread spectrum time-domain reflectometry (SSTDR) (Smith et al. [8], Furse et al. [3]), and noise-domain reflectometry (NDR) (Lo & Furse [4]). STDR launches pseudorandom (PN) codes into a wire under test, and then finds the position of faults by the peaks of correlation traces between the codes and its echo due to the faults. This method is suitable for testing live wires due to the PN code's self-correlation. SSTDR method uses sine-wave modulated PN codes as probe signal in order to expand the bandwidth of codes and then improve the spatial resolution to a few centimeters. However, the unambiguous detection range is limited by the periodicity of PN code. In the method of NDR, noise or high-speed signals on the wires are utilized to locate the distances of faults. The transmission of a specific probe signal is not required, while the application of NDR is restricted by significant noise on wires. Therefore, it is urgent to put forward a more flexible and efficient method to test live wires at present.

Recently, a novel method named chaos time-domain reflectometry (CTDR) has been presented for detecting wire faults (Wang et al. [9], Xu et al. [10]). In this method, a physical chaotic signal from a laser diode or a Colpitts oscillator is used as probe signal, and location of faults are still achieved by a correlation method like the STDR. It has been experimentally demonstrated that the CTDR has several advantages: (1) wideband chaos is easily achieved by utilizing a laser diode or a simple nonlinear circuit to ensure high spatial resolution; (2) the nonperiodic waveform of chaotic signal can realize unambiguous detection. However, its ability of testing live wires is still unknown, which needs to be investigated.

In this paper, we experimentally demonstrate that the CTDR can be used to locate faults on live wires in digital communication systems transmitted the high density bipolar of order 3 (HDB3). We experimentally analyze the effects of the chaotic probe signal on the bit error rate (BER) of the HDB3, and the influences of the backward HDB3 reflected by wiring faults on the signal-noise-ratio (SNR) of CTDR measurement. The experimental setup is described in Sec. 2. Section 3 presents the characteristics of chaotic probe signals. Then, in Sec 4, we report the experimental results of live test. Some conclusions are drawn in Sec. 5.

2. Experimental Setup

The schematic of experimental setup using the CTDR for fault location on live wires is shown in Figure 1. The digital communication system consists of a wire and a bit error rate tester (BERT, CETC AV5233C). The BERT is used as a transmitter that generates a 2/8/34–Mbit/s HDB3, and also as a receiver that receives the signal after travelling on the wire. Meanwhile, the BERT is used to measure the BER of the transmitted digital signal, which is used to evaluate the influences of the proposed CTDR. As shown in the dashed box in Figure 1, the CTDR employs an improved Colpitts oscillator as the source of chaotic probe signals. The output chaotic signal is equally divided into two parts through a power divider (PD, A-INFO GFT2-0.2-1000). One as a reference signal is recorded by an oscilloscope (OSC, LeCroy SDA 725Zi), and the other as a probe signal is enlarged by a variable gain amplifier (AMP, CONQUER KGRF-10). The probe signal is mixed with the HDB3 via the synthesizer (SYN, A-INFO GF-T2-0.2-1000), which is then injected into the tested wires (Belden UMR43). Once the mixed signal touches a fault on wire, it will be partly reflected back. The return signal passes through a T-type connector and then is recorded by the OSC. We can get the correlation curve from the return signal and the reference signal by a computer. From the position of correlation peak, we can judge the location of the fault. If there is no fault, the mixed signal will be totally transmitted to the BERT to calculate the BER.

In our experiments, the bandwidths of PD and SYN are the same ranging from 0.2 MHz to 1000 MHz. The AMP's bandwidth is from 75 KHz to 10 GHz, and its maximum gain and regulation accuracy are 25 dB and 0.5 dB, respectively. The sampling rate and bandwidth of OSC are 5 GSa/s and 1 GHz, respectively. The maximum frequency and characteristic impedance of the tested wires are 1 GHz and (50±2) Ω, respectively.

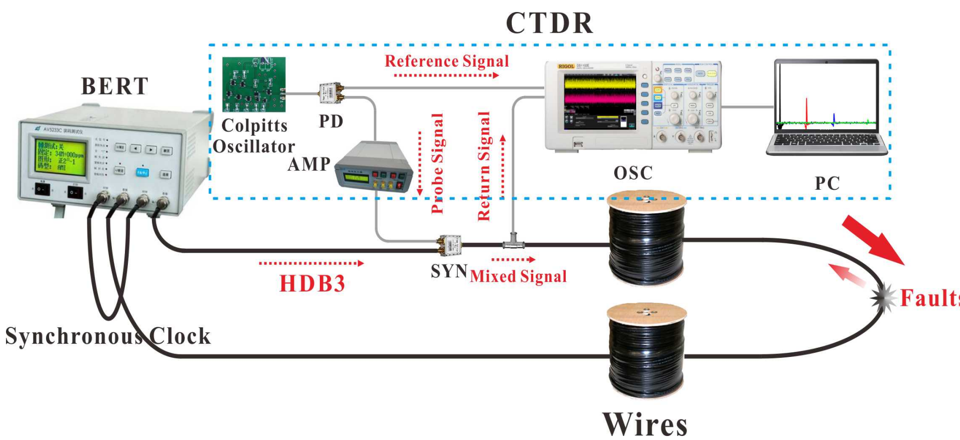

Figure 1. Schematic of experimental setup using the CTDR for fault location on live wires. CTDR: chaos time-domain reflectometry. BERT: bit error rate tester. AMP: amplifier. SYN: synthesizer. PD: power divider. OSC: oscilloscope. PC: personal computer.

3. Characteristics of Chaotic Probe Signals

Figure 2 shows some properties of the chaotic probe signal generated from an improved Colpitts oscillator in the CTDR, when the drive current and voltage respectively are 26.5 mA and 1.8 V. It is noted that the waveform of chaotic signal exhibits a fast but irregular oscillation, as shown in Figure 2(a), where the peak-to-peak value and average power are 160 mV and -12.2 dBm, respectively. This complex chaotic signal has a wide spectrum shown in Figure 2(b), covering frequency from 0 to 2 GHz. If we correlate the chaotic signal, a delta-function-like autocorrelation curve with a narrow peak will be obtained, as presented in Figure 2(c).

In order to explore the suitable chaotic states for the CTDR, we discuss the output characteristics of the improved Colpitts oscillator, which is shown in Figure 3. The output signal undergoes a period-doubling bifurcation route to chaos as the supply voltage increases from 6 V to 14.5 V, as shown in Figure 3(a). Then, we use peak-noise-ratio (PNR) (Xu et al. [10]) of correlation trace to quantitatively evaluate the auto-correlation properties. We can find that, the PNR increases with the increase of supply voltage as Figure 3(b) shows. When the supply voltage reaches 14.5 V, the PNR converges to a maximum value. In this case, the chaotic

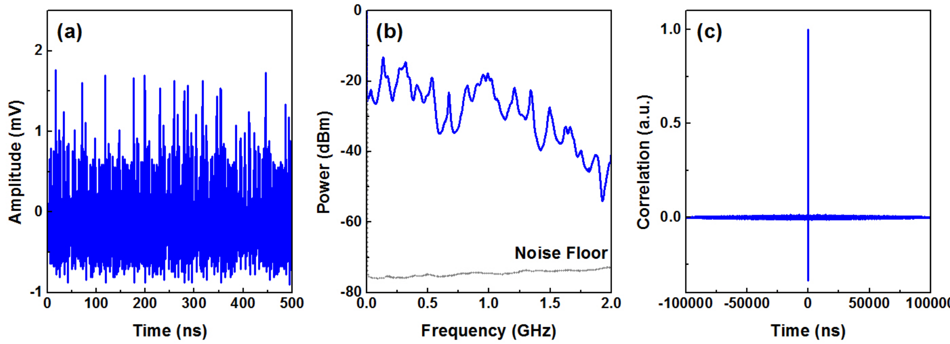

Figure 2. Properties of the chaotic signal generated from the CTDR. (a) Temporal waveform. (b) Power spectrum. (c) Autocorrelation trace.

signal is the most appropriate to be used as the probe signal for locating wire faults.

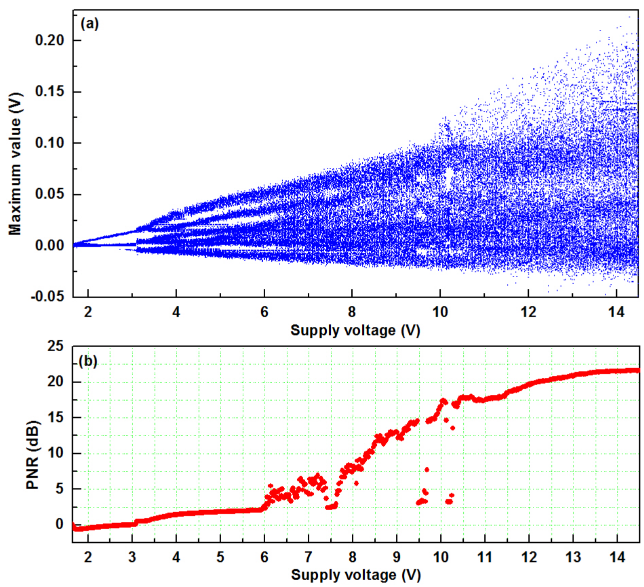

Figure 3. Output characteristic of the improved Colpitts oscillator as the supply voltage increases. (a) Bifurcation diagram. (b) PNR variation.

4. Experimental Results of Live Test

In this section, we first demonstrate that the chaotic signal generated from the CTDR can be injected into the live wires carried the HDB3 by utilizing the SYN. Then, in order to prove that the CTDR can realize fault locations on live wires, we experimentally analyze the mutual effects between the chaotic probe signal and the HDB3 at different rates.

Taking the 34–Mbit/s HDB3 as the transmitted signal, we show its properties in Figure 4. Figures 4(a) and 4(b) separately display the waveform and power spectrum of 34–Mbit/s HDB3 detected by the OSC and a spectrum analyzer. The chaotic probe signal and 34–Mbit/s HDB3 were mixed by the SYN under different power ratios. Then, the mixed signal was transmitted on the tested wire of the digital communication system. Here, power ratio is denoted by chaos-to-signal power ratio (CSR). The waveform and power spectrum of the mixed signal are displayed in Figure 5. The values of CSR we selected were -18.9, -13.5, and -4.0 dB, respectively. Our experiments demonstrate that the amplitude of chaotic probe signal superimposed on the HDB3 becomes stronger with the increase of CSR, as Figure 5(a) shows. Meanwhile, the high frequency energy of the mixed signal gradually increases in the power spectrum as shown in Figure 5 (b), which arose from the chaotic signal. Therefore, the results prove that the CTDR can be embedded into a digital communication system for monitoring the wiring integrity.

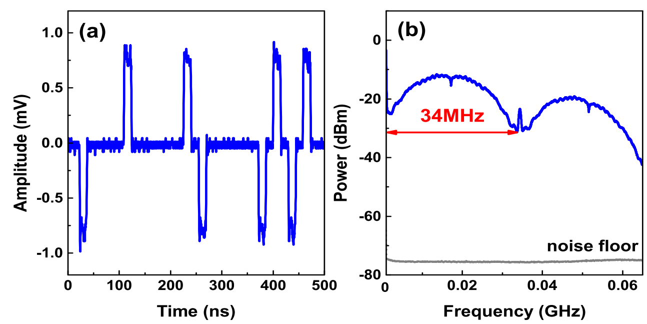

Figure 4. Properties of the 34-Mbit/s HDB3. (a) Temporal waveform. (b) Power spectrum.

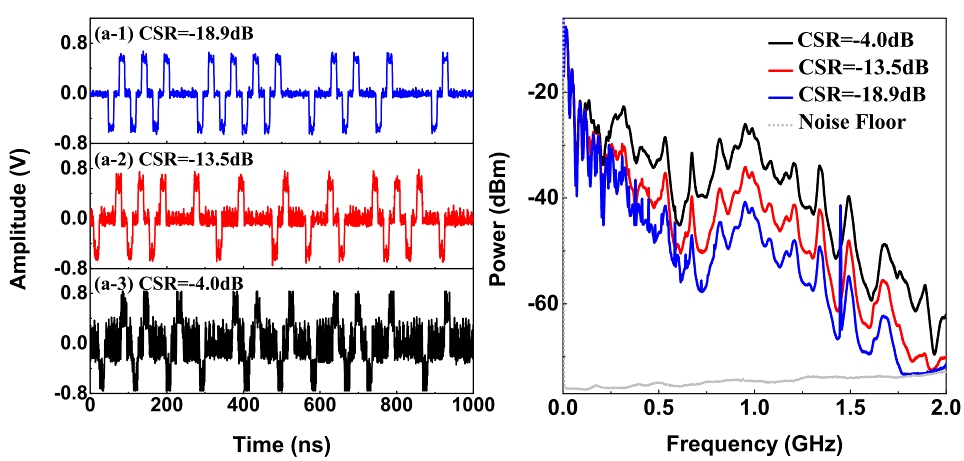

Figure 5. Properties of the mixed signal under different CSRs. (a) Temporal waveform. (b) Power spectrum.

As we stated in Section 2, the effects of the chaotic probe signal on the HDB3 could be judged by the value of BER, which was obtained from the BETR before the fault occurred. It should be mentioned that the BER of the digital communication system under test is 0 without the chaotic probe signal injecting. This indicates that the error code is entirely caused by the CTDR. To study the effects of the chaotic probe signal on the BER of HDB3 at different rates, we chose 2, 8, and 34 Mbit/s HDB3 as the transmitted signal, respectively. The variation tendency of BER with the CSR increasing is shown in Figure 6. The tendency of BER is basically the same, that is, the BER increase as CSR rises regardless of the rates. Nevertheless, a higher rate corresponds to a larger BER under the same CSR.

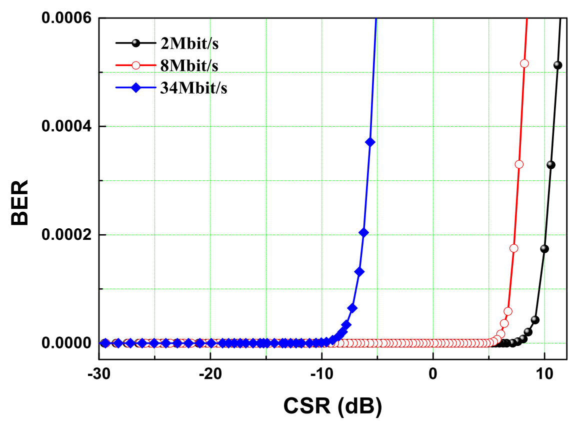

Figure 6. BER as a function of CSR of 2, 8, and 34–Mbit/s HDB3, respectively.

When a fault occurs on the live wires, the CTDR detects the wire fault by correlating the chaotic reference signal and echo signal. The echo signal is formed by the mixed signal back-reflected from the fault. Therefore, we need to investigate the influences of the backward HDB3 reflected by wiring faults on the CTDR measurement. The measurement of CTDR is evaluated by SNR which is defined as

$$\mathrm{SNR} = 10 \times \log_{10}\left(\frac{p}{(\bar{n} + 3 \times \mathrm{std}\,(n))}\right), \tag{4.1}$$

where p and n are the signal and noise values of the correlation trace, respectively. Under the 8.5-dB CSR, we measured a fault (such as an open circuit) at a distance of 100m on a live wire, which separately carried the 2/8/34–Mbit/s HDB3. The detection results of CTDR are displayed in Figure 7. The results show that the fault is apparently located at 100m from the position of the correlation peak. With the rate of HDB3 increasing, the value of SNR becomes smaller. The reason is that a higher rate of HDB3 corresponds to a larger overlap area of chaotic signal energy, leading to a stronger mutual interference.

To further prove that the CTDR can realize the fault location on live wires without disturbing the transmitted signal, we took the 34–Mbit/s HDB3 as the transmitted signal to investigate the scope of CSR. As shown in Figure 6, the BER increases with the CSR increasing. We further analyze the variation tendency of BER and SNR in detail, when CSR ranges from -30 dB to -10 dB. The experimental results are shown in Figure 8. The left border of the green wireframe shown in Figure 8 denotes 3–dB SNR, which is the minimum to precisely predicate the location of the fault. In the green wireframe, the value of CSR is from -24.8 dB to -13.5 dB, and

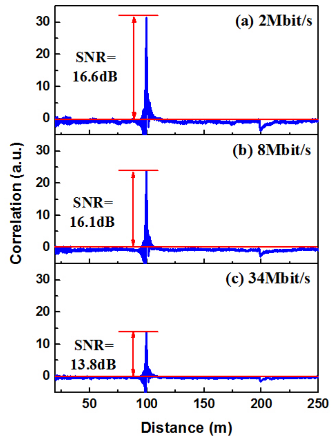

Figure 7. Detection results of the CTDR under the same CSR.

the BER of 34–Mbit/s HDB3 is less than 3E-10, meanwhile the values of SNR are all larger than 3 dB. This suggests that when the power of the chaotic probe signal is about from -24.8 dB to -13.5 dB lower than that of the 34–Mbit/s HDB3, the CTDR can precisely detect the fault location without disturbing the transmitted signal. To further understand the effects of different CSRs on fault locations, we provide three cases corresponding to the arrows in Figure 8 respectively, as Figure 9 shows. The location of fault was set at 100m. Note that the fault was accurately located in the last two cases, meanwhile the BER was enough small. It can be deduced that if the rate of HDB3 is lower than 34 Mbit/s, the range of CSR will be much larger. Our results indicate that the effects of CTDR on the transmitted signal on live wires in the digital communication system are very weak. Meanwhile, the chaotic probe signal has a strong anti-jamming ability, which makes it immune to the transmitted signal on wire.

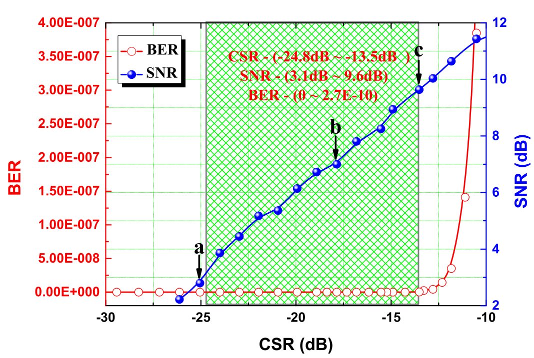

Figure 8. BER and SNR as a function of CSR.

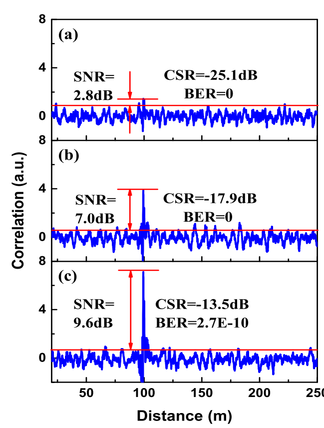

Figure 9. Detection results of the CTDR when the CSRs are -13.5, -17.9, and -25.1 dB, respectively.

5. Conclusion

We propose a CTDR for locating faults on live wires and experimentally demonstrate fault detections on live wires carried the HDB3 with different rates in a digital communication system. The experimental results indicate that fault detection on live wires is achieved when the power of the chaotic probe signal is about from -24.8 dB to -13.5 dB lower than that of the HDB3. In this case, the BER is kept less than 3E-10, and the SNR of CTDR is higher than 3 dB. As demonstrated, the CTDR can realize real-time monitoring on live wires and locate wire faults timely and accurately. It is reasonably concluded that the CTDR has a promising future for diagnosis and maintenance of wiring systems.

Acknowledgments

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