Digital Measurement of Human Proximity to Electrical Power Circuit by a Novel Amplitude-Shift-Keying Radio-Frequency Receiver

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Abstract— **An electrical injury protection system is being developed to protect electrical workers from electrical injury and electrocution by human proximity and electrical contact sensing. Proximity is monitored by the insertion loss of radio-frequency (RF) transmission between the power circuit and the human body. The system continuously transmits low power amplitude-shift-keying (ASK) RF waves from the power circuit to the surrounding area. An RF receiver attached to the human body measures the magnitude of incoming ASK RF waves which is inversely related to the proximity of the human body to the power circuit. A novel digital ASK demodulation method is used to efficiently conduct digital measurements of the incoming ASK RF wave magnitude. In this method, the RF receiver converts the incoming ASK signals to saw-tooth-like enveloped ASK RF signals. A digital ASK demodulator demodulates the converted RF signal and digitizes the saw-tooth-like envelopes into square waves with their pulse widths directly related to the magnitude of the incoming ASK RF signals. The wider the pulse width, the stronger the incoming RF wave, and vice versa. Human proximity and electrical contact are digitally detected by counting the width of the demodulated pulses. The current consumption of the prototype receiver is only 9 microamperes which is 1600 times less than that for a conventional ASK magnitude detector.**

I. INTRODUCTION

Occupational electrical fatalities were ranked 5th among the U.S. national occupational fatalities during 1990-1999, with 7,271 occupational electrocution deaths [1]. In order to address this occupational risk factor, an electrical injury protection system is being developed by the National Institute for Occupational Safety and Health (NIOSH). The goal of the system is to protect electrical workers from being electrocuted by live low-voltage (<600 V) electrical power circuits. The system is designed to detect human-body proximity and electrical contact to a power-circuit by monitoring the insertion loss of radio-frequency (RF) transmission between the power circuit and the human body. The system activates warning alarms if human proximity is detected, and immediately trips the circuit-breaker and existing ground fault circuit interrupters when electrical contact is detected [2].

The human proximity detection mechanism of the system consists of a Controller which is plugged into a nearby electrical receptacle on a live power circuit, and a Body-Device which is worn by an electrical worker working near the power circuit. The Controller contains a low power Amplitude-Shift-Keying (ASK) RF transmitter which continuously transmits omni-directional ASK RF waves to the surrounding area. The Body-Device, which includes an ASK RF receiver with its receiving antenna attached to the worker's body, receives the ASK RF waves and measures the magnitude of the incoming RF signal for human proximity and electrical contact detection. The magnitude of the incoming RF signal, which is inversely related to the distance between the worker's body and the power circuit, is used by the receiver as a human proximity indicator. The greater incoming RF signal magnitude is recognized by the Body-Device as closer proximity of the human body to the power circuit, and vice versa [3, 4].

In order to enable the embedded microprocessor in the Body-Device to convert the received RF signal magnitude to a related range of human proximity to the power circuit, it is necessary for the receiver to digitally measure the magnitude of incoming RF signal, and output the numerical RF magnitude to the microprocessor. Because the receiver is a continuously-on battery-powered device, its current consumption is limited to a very low level of 1~2 milliamps. A conventional method for digitally measuring ASK RF signal magnitude is: first, to demodulate the analog envelopes from an ASK RF signal, and then, to use an analog-to-digital converter (ADC) to convert the analog amplitude of the demodulated envelopes to digits [5]. This method requires an analog envelope demodulator which consumes much more current (15 mA) than the current consumption limit required by the battery-powered Body-Device receiver [6]. Further, this method needs an ADC for analog-to-digital conversion which also consumes extra battery current (0.1 – 0.6 mA). Because of the high battery power consumption, the conventional methods for measuring ASK RF signal magnitude are not suitable for the battery-powered Body-Device receiver.

In order to reduce the current consumption in digital measurement of ASK RF signal magnitude, a novel power efficient

This project is supported by National Institute for Occupational Safety and Health research fund.

digital ASK demodulation method is implemented in the Body-Device receiver. This new method demodulates the variable magnitudes of the incoming ASK signals to square waves with variable pulse width. Human proximity to the power circuit can be determined by digitally measuring the pulse widths of the demodulated square waves. This method allows the substitution of the power consuming analog ASK demodulator with a digital ASK demodulator which could be much more power efficient than the analog one [6, 7]. In addition, this method eliminates the ADC used in conventional methods, which further reduces the receiver current consumption.

II. METHOD

A. Concept of Digital ASK Demodulation Method and the ASK RF Receiver Configuration

This method intends to use a digital ASK demodulator for reducing the receiver current consumption. Conventionally, a digital ASK demodulator could not be used for ASK signal magnitude measurement, because its demodulated ASK envelopes are a stream of square waves which contains no magnitude information. To address this problem, an envelope converter is applied before the input of the digital ASK demodulator. The converter converts the incoming square-wave enveloped ASK RF waveforms to saw-tooth-like enveloped ASK waveforms. The saw-tooth-like envelopes are demodulated and digitized by the digital ASK demodulator. The internal slicing threshold of the digital ASK demodulator slices the saw-tooth-like envelopes into square waves with variable pulse widths. The width of the pulses is directly related to the magnitude of ASK envelopes. A fixed slicing threshold digitizes a saw-tooth-like envelope with a greater magnitude to a square wave with wider pulse width, and digitizes an envelope with a smaller magnitude to a square wave with narrower pulse width.

As shown in Fig. 1, the ASK RF receiver in the Body-Device consists of a receiving antenna which is composed of a pair of conductive-fabric cuffs tightened to the worker's wrist, a saw-tooth envelope converter which converts square-wave enveloped ASK signals to saw-tooth-like enveloped signals, a digital ASK demodulator which demodulates the saw-tooth-like enveloped ASK signals, and digitizes the demodulated saw-tooth-like envelopes to square waves, a pulse-width counter which measures the pulse width of the demodulated ASK signal, and a pulse-width to proximity converter to convert the pulse width to a human proximity distance range.

During human proximity detection, the Controller continuously transmits ASK RF waves through the power circuit to the air. The carrier frequency of the ASK signal is modulated by a 1 kHz square wave, as shown in Fig. 2a. As the worker is within the proximity detection range surrounding the power circuit, the ASK receiver antenna pair picks up the incoming ASK RF waves transmitted through the worker's body to the antenna. Notice that the ASK waveforms in Fig. 2a have different magnitudes, from the smallest magnitude on the left-hand side to the greatest on the right-hand side. The received ASK RF signals are sent to the saw-tooth envelope converter which is composed of an impedance inverter and an LC band-pass filter with a narrow passband. The impedance inverter matches the relatively lower impedance of human skin with the higher input impedance of the digital ASK demodulator. The bandpass filter filters out the noise and other interference frequencies. With its narrow passband, the group delay of the filter is nonlinear which distorts the envelope of the incoming ASK RF wave, and converts square-wave enveloped ASK RF signal (Fig. 2a) to ASK RF signals with sloped leading and trailing envelope edges. The bandwidth of the filter is carefully selected so that the filtered ASK envelopes have their leading and trailing edges shaped similar to a saw-tooth wave as shown in Fig. 2b. The digital ASK demodulator demodulates the saw-tooth-like envelopes (Fig. 2c), and digitizes the demodulated envelopes into square waves with their pulse width directly related to the magnitude of the incoming RF signal. Since smaller magnitude envelopes have less of their envelopes above the slicing threshold than envelopes of greater magnitude, the converted square waves have narrower pulse widths than those with greater magnitude, as shown in Fig. 2d. The pulse-width counter and the pulse width to proximity converter are functioned by the embedded microprocessor firmware program. As the demodulated square waves enter the input of the pulse-width counter, the counter numerically counts the pulse width. The pulse-width to proximity converter converts the pulse widths to one of the five human proximity ranges (No signal, Far, Medium, Near, Electrical Contact) by using an empirical conversion algorithm.

B. Experiment Setup for Human Proximity Measurement

An experiment was setup to examine the feasibility of using the digital ASK demodulation method to measure the magnitude of the incoming ASK RF signal. An ASK RF receiver using digital ASK demodulation method has been designed, fabricated, and is currently being calibrated and modified. An AS3931 programmable low-frequency ASK wakeup receiver (Austriamicrosystems) [7] was selected as the digital ASK demodulator of the ASK RF receiver because of its ultra-low current consumption (9 micro amperes in typical working condition).

The receiver's carrier frequency was selected to be 141.6 kHz. The results of human subject tests on RF transmission between a human body and an electrical power circuit indicate that the radio frequencies between 100 and 200 kHz are optimal for human proximity detection. In this frequency range, the RF transmission insertion loss between a human body and a power circuit monotonously increases with the greatest loss gradient as the human body moves away from the power circuit [2, 3].

The saw-tooth envelope converter is composed of a LC filter

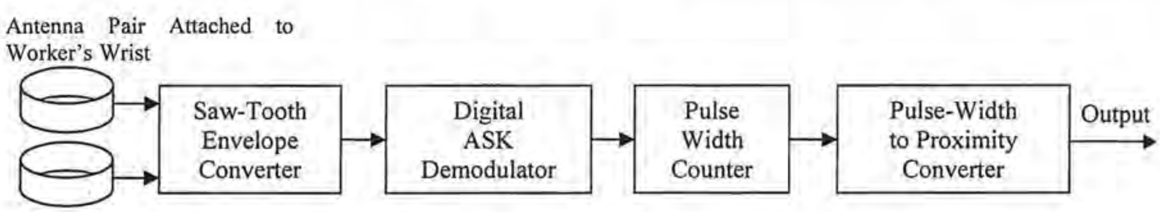


Figure 1. Configuration of the Body-Device digital ASK RF receiver.

with a secondary coil for impedance inversion. The quality factor of the primary coil is about 72. Using (1), the bandwidth (BW) of the filter is calculated to be about 2 kHz at the carrier frequency of 141.6 kHz.

$$BW = \frac{f_0}{Q} \tag{1}$$

Simulated ASK RF signals are generated by an Agilent E4221 signal generator with the carrier frequency of 141.6 kHz which is modulated by square waves. The frequency of the modulation square waves is 1.0 kHz which should not exceed the filter bandwidth (2 kHz). The pulse width was chosen to be 52 μS in order to obtain saw-tooth like waveform as the ASK signals pass the envelope converter.

III. Results and Discussion

As the simulated ASK RF signal passes the envelope converter, the ASK envelopes are converted from square waves to saw-tooth like envelopes, as shown in Fig. 3. Fig. 3a shows a converted ASK waveform with 150 mV of the input ASK amplitude (the proximity ASK signal strength is generally below 3 mV. The input signal amplitude was tuned to 150 mV, so that the converted envelopes are visible on the oscilloscope). The input amplitude in Fig. 3b is 5 times smaller (30 mV) than that in Fig. 3a. With the scope vertical scale in Fig. 3b tuned to 5 times more sensitive than that in Fig. 3a, the amplitude of the signals in Fig. 3b look similar to that in Fig. 3a. Notice that the proportion of the device noise floor to the amplitude of the saw-tooth-like envelopes is greater in Fig. 3b than that in Fig. 3a. This noise-floor proportion increases as the amplitude of the input ASK signal decreases. This variable noise floor proportion enables the AS3931 demodulator to digitize the demodulated saw-tooth-like envelopes with variable pulse width. Since the AS3931 demodulator uses an adaptive slicing threshold, rather than the fixed slicing threshold mentioned above, to digitize analog envelopes, its slicing threshold level is variable. The slicing threshold in the AS3931 is determined by the average of the input envelope amplitude. With the higher noise-floor proportion in smaller-amplitude input signal than that in greater-amplitude input signal, the adaptive slicing threshold determined by smaller-amplitude input signal mixed with the device noise is closer to the peak of the demodulated envelope than that determined by greater-amplitude input signal mixed with device noise. This device-noise modified slicing threshold ensures that the AS3931 can digitize the saw-tooth-like envelopes to square waves with their pulse width directly related to the input ASK signal amplitude.

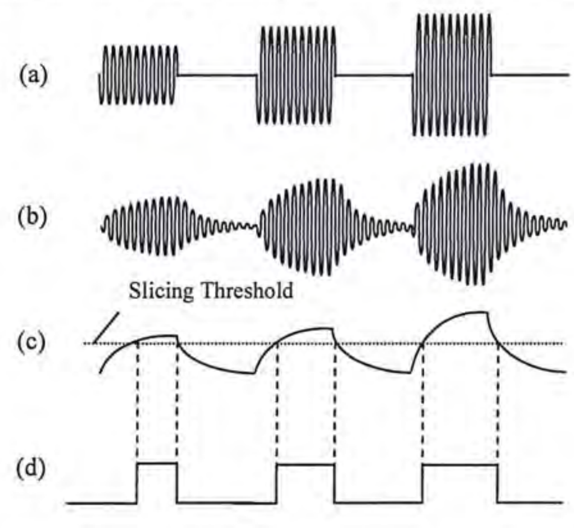


Figure 2. Waveforms in digital ASK demodulation concept.

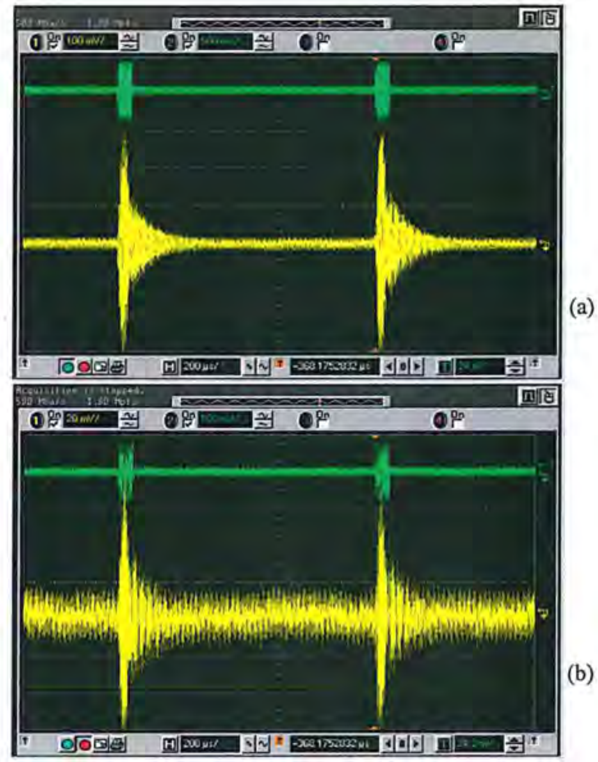
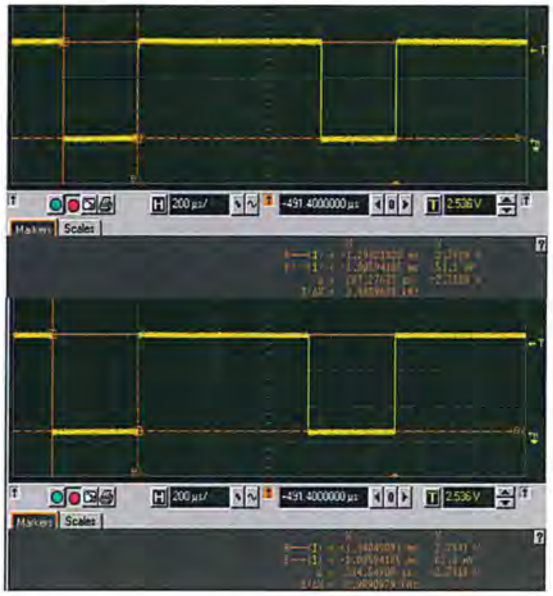


Figure 3. The square enveloped ASK signal is converted to saw-tooth-like enveloped ASK signal after passing the envelope converter. Input ASK signal amplitude: (a) 150 mV, (b) 30 mV [with scope scales 5 times more sensitive than that in (a)].

The digitized square waves are shown in Fig. 4, with their pulse width directly related to the magnitude of the input ASK RF waves. The amplitude of the input ASK RF signal is smaller (50 μV) in Fig. 4a than that (500 μV) in Fig. 4b. Respectively, the (negative) pulse width of the demodulated square waves is narrower (287.3 μV) in Fig. 4a than that (334.5 μV) in Fig. 4b. The pulse width difference is 47.3 μV.

The pulse width of the digitally demodulated ASK RF signals versus the amplitude of their RF inputs in the range between 20 μV to 1 V is shown in Fig. 5. Table 1 shows the input ASK voltage versus the equivalent human proximity to power circuit. Combining the mean and standard deviation pulse widths in Fig. 5 with the equivalent proximity in Table 1, it can be seen that this new demodulation method detects electrical contact and the human proximity up to 40~60 cm. The amplitude to pulse-width conversion accuracy varies from 1.8 % at 10 mV of ASK input amplitude to 10.8 % at 20 μV. As the input ASK signal decreases to 20 μV, the demodulated pulse width no longer monotonously shrinks. This abnormal input-amplitude output-pulse-width



(a)

(b)

Figure 4. The digitized saw-tooth-like envelopes. (a) input ASK amplitude = 50 μV, pulse width = 287.3 μS. (b) input ASK amplitude = 500 μV, pulse width = 334.5 μS.

relationship at 20 μV input level may be attributed to the effect of increased proportion of device noise-floor to the input ASK amplitude. Excluding the receiver output at 20 μV input level, the receiver is able to effectively detect the electrical contact and human proximity to a power circuit in the range between circuit insulation to 5 ~ 25 cm. The addition of a low-noise preamplifier in front of the envelope converter may be necessary to increase signal-to-noise ratio and receiver sensitivity, hence to increase the human proximity detection range.

TABLE I. INPUT ASK MAGNITUDE VS. EQUIVALENNT HUMAN PROXIMITY TO POWER CIRCUIT (CALCULATED FROM PRESENTATION DATA IN [4])

Input Volt. (μV)	3000	1000	100	50	20
Equivalent Proximity	Electrical Contact	Circuit Insulation	Insulation ~ 2 cm	5 ~ 25 cm	40 ~ 60 cm

IV. CONCLUSIONS

This new digital ASK demodulation method consumes only 9 micro amperes of current, which is 1600 times less than the current consumption in a conventional demodulation method. This method can effectively detect electrical contact and human proximity to the power circuit in the range between circuit insulation and 5 ~ 25 cm. It is currently implemented in the Body-Device RF receiver for digital measurement of human proximity to the power circuit, and is considered as the best measurement method to conserve the device battery power. In order to enlarge the human proximity detection

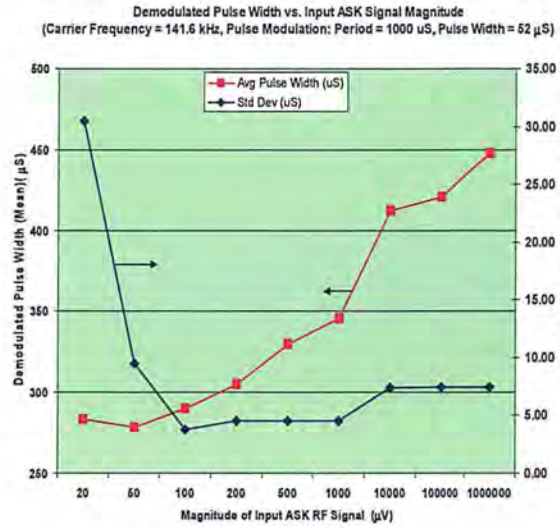


Figure 5. Mean and standard deviation of the demodulated pulse widths versus the magnitude of input ASK signals.

range, it is necessary to further improve the demodulation sensitivity of this method.

ACKNOWLEDGMENT

The authors would like to thank Mr. Bradley H. Newbraugh for his electronic hardware assistance.

DISCLAIMER

Mention of the name of any company or product, or inclusion of any reference, does not constitute endorsement by the National Institute for Occupational Safety and Health.

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