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I am submitting herewith a thesis written by David R. McNeilly entitled "Development of a Wire Identifier and its Application to a Thermocouple Instrumentation System." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.

T. V. Blalock

T. V. Blalock, Major Professor

We have read this thesis
and recommend its acceptance:

E. J. Kennedy

J. M. Hoag

M. J. Rohrer

Accepted for the Council:

C. W. Mink

The Graduate School

DEVELOPMENT OF A WIRE IDENTIFIER AND ITS APPLICATION
TO A THERMOCOUPLE INSTRUMENTATION SYSTEM

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

David R. McNeilly

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DEDICATION

To my wife, Sandy, and my daughters, Jennifer and Holly.

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ABSTRACT

Any large electrically controlled system (i.e., a nuclear reactor) has an elusive problem of assuring all wires are connected correctly. Improperly connected wiring could cause misleading results, property damage, or even loss of life. One possible method of insuring proper wiring installation in a large system is to provide a means for each sensor in the system to identify itself when interrogated. The identification is accomplished by applying a signal to a sensor wire pair in a control room to which a specially equipped sensor would respond. An interrogator and sensor identifier would allow a user to monitor the system wiring as often as desired establishing some confidence in the system wiring.

This thesis proposes and develops a wire identification system with an acceptable operating frequency range of 1 kHz to 1 MHz for a two foot thermocouple line connecting the interrogator to the specially equipped sensor. Varying the type and increasing the length of the connecting wire between the identifier and the interrogator may further limit this frequency range. The developed identifier system is shown to properly identify specially equipped thermocouple connectors with various cables and the frequency limitations imposed by these cables are analyzed. The identifier, incorporated into the thermocouple system, interferes with the temperature measurement only during wire identification. This thesis may be used as a base for further experimental work required for a viable identifier system.

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CHAPTER 1

INTRODUCTION

All large systems have quality assurance problems. Failures in the systems may cause consequences such as power failures or even loss of life. For instance, in recent years, many problems have arisen in large aircraft systems; engine failures, engine detachment in flight, tools left in engine's intakes, flammable seat cushions. Other examples of quality assurance problems can be found in the Three Mile Island nuclear power plant accident where several "fail-safe" devices were not really fail safe. The consequent "nuclear melt-down" scare severely crippled the nuclear power industry. The obvious solution in most cases is to check all parts of a large system initially and periodically to assure their functionality.

In large electrical or electrically controlled systems, there are thousands of electrical wire pairs with combined lengths of miles. A complete system wiring check requires man-years of time and costs millions of dollars. Even with the wiring check, there is no assurance that all wires have been examined. Before a large system can be brought on line, therefore, a double check needs to be made of the system to help eliminate wiring errors. Periodic wiring checks are needed to assure that no wires have been broken or improperly connected during maintenance. Recently, many utilities have taken a loss and withdrawn from the nuclear power industry because of high costs generated from trying to meet the Nuclear Regulatory

Commission's demands for quality assurance. A large part of this cost is in quality assurance of electrical wiring. According to Instrumentation and Control records kept at Oak Ridge National Laboratory [1], at least 50% of the cost of installation of instrumentation in a nuclear reactor is wiring costs.

Ensuring that electrical wiring is initially installed correctly is a perplexing and elusive problem. If the system wiring could be monitored, however, system wiring could be verified periodically. Adding monitor wiring, however, requires increasing the system wiring which increases the possibility of wiring errors. Monitor wiring errors could be minimized by keeping all of the monitor wiring inside a control room.

A computer could determine the existing instrument-sensor interconnection by connecting the computer to the instrumentation wiring and installing some type of identifier in the sensor connector. Any portion of the sensor wiring identification system that did not respond properly to interrogation by the computer could then be checked. Since a computer could interrogate each sensor wire pair to determine the sensor-instrument interconnection and the computer could contain any given scaling and offset correction information pertinent to both the sensors and their instrumentation, the need for a complete calibration of instrument sensor systems in situ could perhaps be eliminated or at least minimized.

Many of the costs associated with initial wiring installation and wiring diagram generation could possibly be eliminated if this

system were used. The computer could also help to assure the system integrity by periodically verifying proper sensor wire pair interconnection between instrument and sensor and alert maintenance personnel to any changes in system wiring.

Since the primary purpose of system wiring is to transmit information or energy from one location to another, the most desirable wire identification system would not interfere with the information or energy transmitted across the wire pair. For this reason, the objective of this thesis is to develop an operating prototype wire identifier system which would have a minimal affect on the information on the line and could later be further developed into a commercial wire identification system. The identifier system will be tested by incorporating it into a thermocouple temperature measurement system and observing how the two systems interact.

The thesis is divided into six chapters with this introduction being the first chapter. Chapter two describes three initial proposals for a wire identification system and forms a basis for the development of a prototype identifier system. Chapter three describes the development of a prototype wire identification system. Chapter four examines the theoretical frequency limitations of the identifier system to determine its maximum allowable operating frequency. Chapter five experimentally determines the functionality of the identifier and compares the theoretical frequency limitations to measured frequency limitations. Chapter six presents some possible problems to be solved before a commercial wire identification system can be manufactured.

CHAPTER 2

BACKGROUND IDEAS FOR DEVELOPMENT OF A SENSOR IDENTIFIER

As the need for some means of sensor identification became obvious, three different methods of sensor identification have emerged. The operation, advantages, and disadvantages of each of these methods will be discussed in this chapter. The three types of wire pair identifiers discussed will be referred to as (1) the crystal identifier, (2) the serial identifier, and (3) the fixed-frequency identifier.

Crystal Identifier

The crystal identifier system [2] (Figure 2-1) consists of a sensor identifier exciter, a decoder, and a sensor identifier. The sensor identifier exciter applies a voltage to the sensor wire pair to be interrogated. The sensor identifier then responds with a code consisting of signal voltages at certain known crystal frequencies. The decoder converts this frequency information into a digital code which is sent serially to the computer. The sensor identifier exciter may be either a swept frequency oscillator or a voltage pulse generator. The identifier consists of selected crystals placed inside the sensor connector across the two wire line. If the swept frequency voltage generator is used, the decoder would respond when large voltage amplitudes are detected as the generator sweeps through its frequency range, indicating the presence of certain resonant frequencies generated by the crystal in the identifier. If this mode

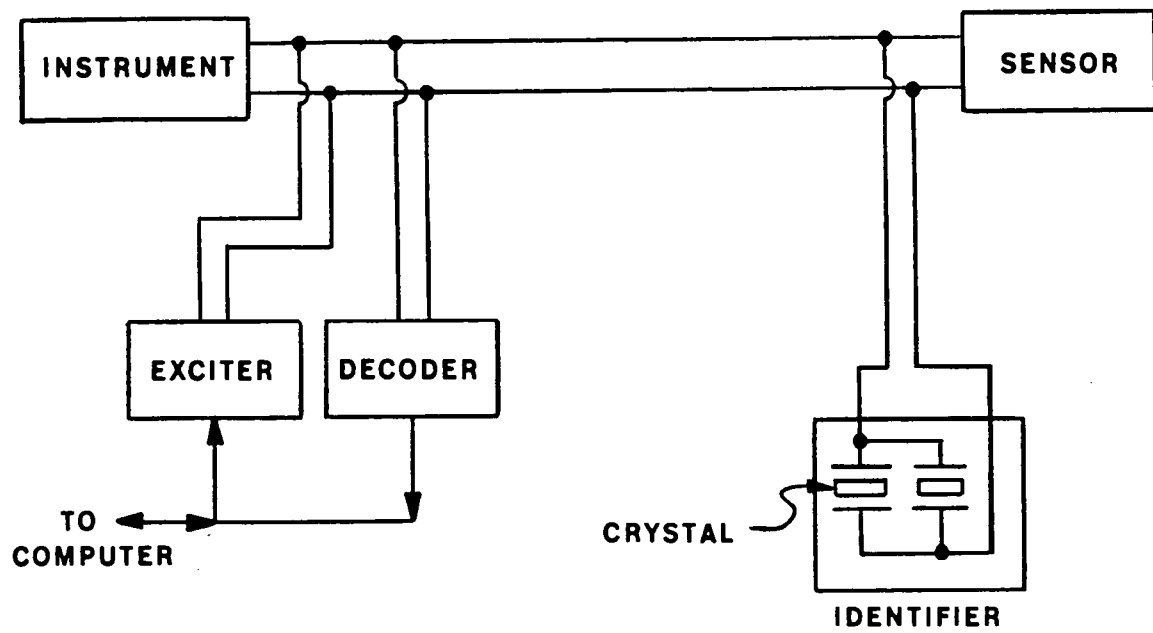


Figure 2-1. Crystal identifier system.

of operation were used, considerable time would be needed to identify each sensor. When periodic wiring checks are desired and thousands of sensors are in the system, sensor identification may need to be made more quickly than the swept frequency mode of excitation would allow. Decoding is not trivial for this mode of operation since the frequency of the excitation voltage must be constantly monitored so that when a crystal in the identifier is detected, its frequency is known. If a high voltage pulse generator were used as a sensor identifier exciter, the decoder would scan the frequency spectrum of the identifier's voltage response to determine the resonant frequency of the crystals present in the identifier. If this mode were used, however, the high voltage pulse needed to insure the crystals in the sensor identifier at the other end of the wire pair are resonating could damage sensor instrumentation connected to the wire pair or the high voltage pulse could interfere with the operation of nearby instrumentation. Decoding of the pulsed voltage mode of operation is not easy because a frequency spectrum analysis must be quickly performed since the crystals respond only for a short period of time.

The advantages of the crystal identifier are as follows:

(1) the sensor identifier requires no internal dc voltage power supply, (2) the identifier excitation voltage is applied through the sensor signal lines so no additional wiring is needed to install the identifier, and (3) the crystal identifier circuitry is simple since it consists only of crystals connected in parallel across the two wire sensor line. Most of the measurements in many large facilities

are low frequency voltage measurements from such devices as thermocouples, and the presence of crystals across the two wire sensor line should not affect the low-frequency impedance characteristics of the sensor-instrument wire pair. The identifier excitation may be capacitively coupled into the sensor wire pair which would help keep the identification process from making dc voltage changes in the sensor wire pair. However, rectification of the excitation frequency due to nonlinearities at the junction of dissimilar metals in the line may cause some dc voltage errors in this system.

The crystal identifier has several disadvantages also: (1) the transmission line impedance of the sensor wire pair may cause erroneous resonant frequencies to be decoded, giving misleading data. To alleviate this problem, the sensor wire-pair impedance must be characterized for each sensor, and (2) the sensor must be isolated from the identifier circuitry at all decoding frequencies, requiring either a frequency isolation circuit for each crystal in an identifier or a method of disconnecting the sensor from the wire pair during the identification process. If a thousand sensors are to be identified, ten frequencies would be needed since the number of crystals needed (n) is related to the number of identified sensors (m) by

$$m = 2^n - 1. \quad (2-1)$$

This large number of crystals needed for each sensor identifier would cause the identifier to be physically large and difficult to incorporate in a sensor connector.

Serial Identifier

The serial identifier system [3] (Figure 2-2) consists of an oscillator, a shift register, and a sensor identifier. When the computer selects the sensor wire pair to be identified, an oscillator applies an ac voltage to the sensor wire pair. The identifier circuitry rectifies the voltage and uses the dc voltage acquired to supply power to the serial logic in the identifier. After the dc power voltage has been developed in the identifier, the voltage oscillator is disconnected from the sensor wire pair and a shift register is connected to the wire pair. The sensor identifier detects the removal of the ac voltage and applies a logic serial voltage code to the sensor wire pair. The sensor identifier also contains an oscillator which drives the identifier's shift register. The serial code set by the identifier is detected by a shift register at the other end of the wire pair and passed along to the computer.

The serial identifier system has many advantages. Increasing the number of sensors to be identified does not significantly increase the identifier hardware. For every additional eight serial bits desired, a shift register must be added but shift registers can be CMOS devices and could easily be incorporated on a monolithic integrated circuit. In fact, the entire serial identifier could be designed small enough to be implemented on a single integrated

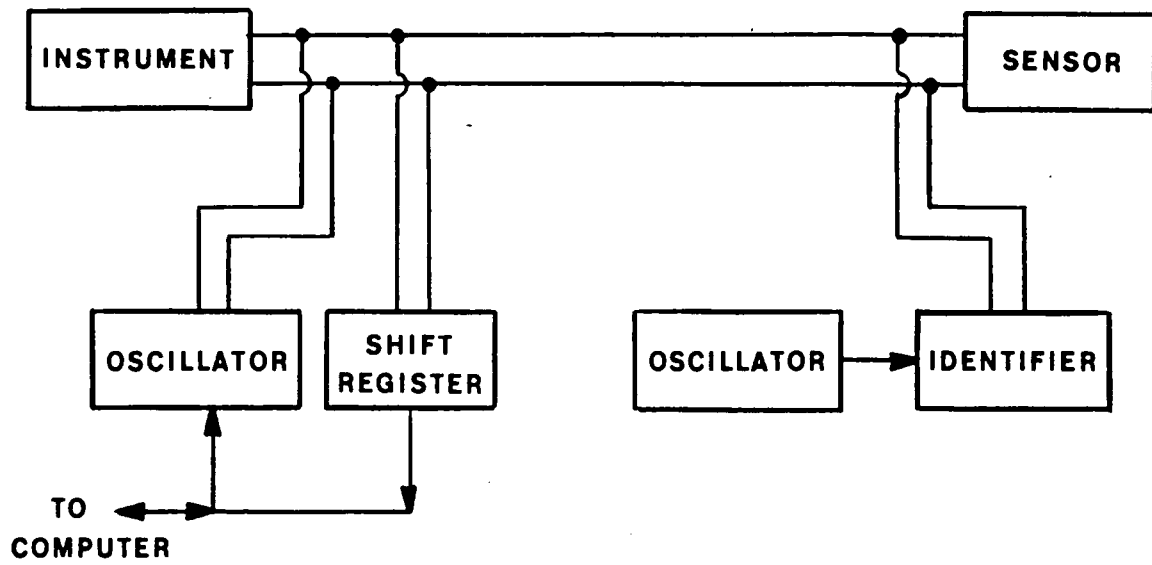


Figure 2-2. Serial identifier system.

circuit and mounted in the connector of the sensor. Decoding the serial word sent by the identifier would be simple. A Universal Asynchronous Receiver Transmitter (UART) or a shift register could be connected to the sensor wire pair during identification to interface the identifier to the computer. The serial identifier requires no additional cabling to the sensor, since power and the serial identification code pass over the sensor wire pair.

However, the serial identifier has several significant disadvantages. Since voltage pulses are applied to the sensor wire pair, the sensor instrumentation connected to the sensor wire pair must be disconnected or isolated from the wire pair during the identification process. Obviously, information generated during the identification process by this instrumentation must be identified and ignored. If the sensor is a low impedance device, such as a thermocouple, the serial voltage code generated by the sensor identifier, as well as the power generation oscillator voltage, may be shorted by the sensor. A method of disconnecting or isolating the sensor from the sensor wire pair during the identification process and not affecting the normal dc impedance and voltage characteristics of the sensor wire pair is not a trivial problem. The serial identifier can only transmit as long as its dc power supply circuitry remains charged, limiting both the length of the serial code and the number of times that code may be transmitted without recharging the identifier power supply.

Fixed Frequency Identifier

The fixed-frequency identifier [4] (Figure 2-3) consists of a wire pair identifier, a fixed-frequency voltage detector, and a serial voltage encoder. The computer outputs a serial voltage code which selects the sensor identifier to excite the wire pair. The selected sensor identifier then applies a fixed-frequency voltage signal to the sensor wire pair. The identifier acquires power to generate this signal from the serial input line connected to it from the computer. A detector at the instrument end of the sensor wire pair responds to the applied signal by selecting a serial voltage encoder which generates a serial code indicative of the instrument to which the excited wire pair is connected.

The fixed frequency voltage identifier has many advantages. The sensor wire pair is subjected to a voltage of only a single frequency, making the isolation of the sensor from the identifier during identification easy to accomplish. The low frequency characteristics of the sensor wire pair can be almost unaffected by the identifier since the identifiers can be capacitively connected to the sensor wire pair. The detection circuitry may be as simple as a passive resistor capacitor filter network. The identifier can be completely designed with CMOS technology which minimizes power consumption and allows a small package.

The greatest disadvantage of the single frequency identifier is that the cabling has to be doubled outside the control room because

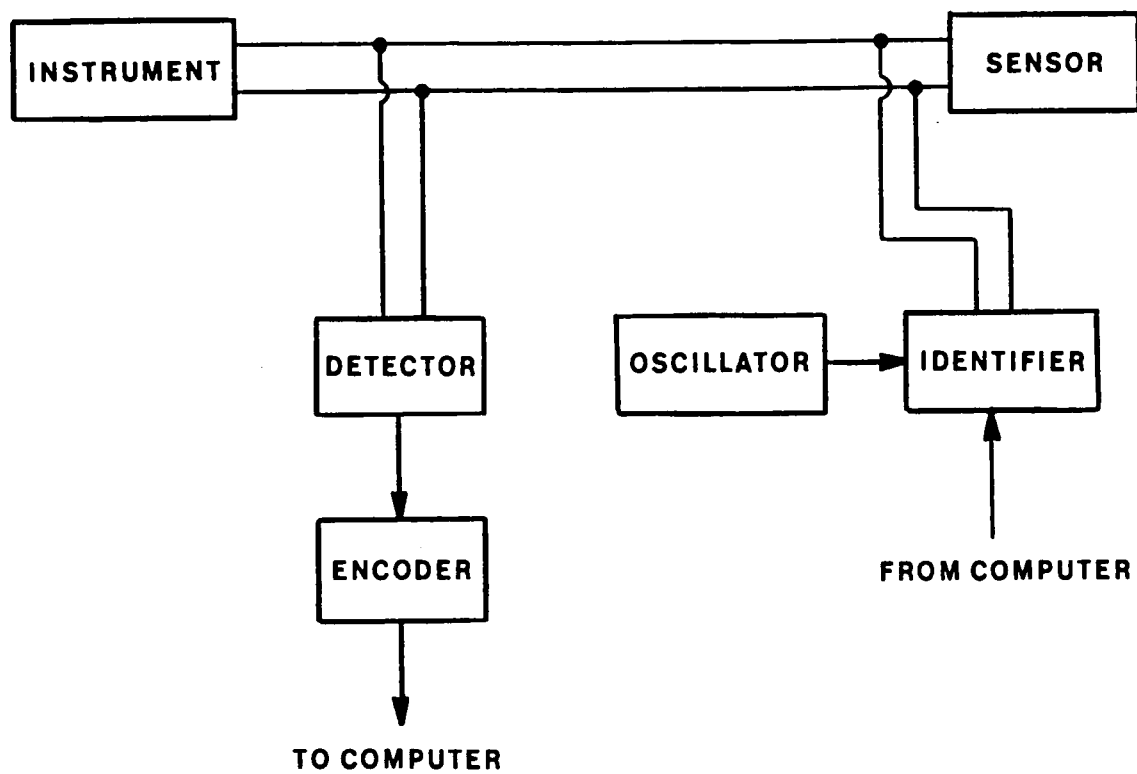


Figure 2-3. Fixed frequency identifier system.

the computer has to directly communicate with both the sensor identifier and the instrumentation for the sensor. This constraint makes this identifier impractical to implement.

Considering the three types of previously proposed identifiers (crystal, serial, and fixed-frequency voltage identifiers) and their particular disadvantages, none are ideally suited for a sensor identifier system.

CHAPTER 3

DEVELOPMENT OF A SENSOR IDENTIFIER

In this chapter the development of a new proposed operating sensor identifier system will be discussed [5]. The sensor identifier power supply and the method of identifier encoding are considered first. Next, the associated drive and decoding circuitry and the computer to receive and display sensor types and numbers are discussed.

Power Supply Development

The method of applying power to the sensor identifier is the first major consideration in developing a sensor identifier system. The serial identifier discussed in the last chapter had the best means of getting power to the sensor identifier because it does not require additional wiring. A voltage oscillator applies an ac voltage to a sensor wire pair. When the ac voltage is removed from the wire pair, the sensor identifier responds with its serial code. The crystal identifier does not require dc sensor identifier power to be supplied, but large voltage pulses or a swept frequency voltage must be applied to the line to allow the crystal frequencies to be detected. This wideband signal could easily interfere with measurements being made by instrumentation attached to the line. The other disadvantages of the crystal system have been discussed; therefore, it was rejected as a method of identification.

Even with the scheme used in the serial identifier system for developing dc sensor identifier power, many disadvantages arise when an ac voltage is used to charge the identifier power circuitry. The length of the sensor identifier's transmitted, serial code is constrained to the time the identifier's power supply can hold its dc voltage in the operating region for the logic circuitry of the sensor identifier and the serial transmission rate. The voltage amplitude of the serial pulses transmitted by the sensor identifier will be decreasing as the identifier's dc power supply discharges. The sensor identifier's ability to drive the sensor wire pair is constrained by energy storage capabilities of its power circuitry. For a multi-channel system where hundreds of sensor wire pairs exist and the computer can not be dedicated to scanning sensor wire pairs, the time required for single sensor identification needs to be minimized. Developing dc power in each sensor identifier increases the time needed to make a complete wiring check. If cables are long, much of the energy for the sensor identifier's dc power supply is lost in the sensor wire pair. The ac voltage applied to the sensor wire pair to develop the identifier's dc power may interfere with the instrumentation connected to the line or may be transmitted to other cables interfering with other instrumentation.

The power circuitry for the sensor identifier has many constraints. The power circuitry must use few components since the sensor identifier will be implemented as a monolithic chip. The sensor identifier's power circuitry must be efficient to reduce

energy loss and minimize the time needed to develop dc power. The identifier should develop power and operate from low ac voltages because high amplitude ac voltage could destroy sensitive instrumentation connected to the line. The amplitude of the ac voltage could be minimized by using a voltage multiplication circuit to supply ac power to the identifier. When the sensor connected to a wire pair has low impedance, some means of isolation must be provided between the identifier and the sensor to prevent attenuation of the ac voltage applied across the wire pair.

The first part of the actual development of the sensor identifier was to determine what type of electrical components would be used for the sensor identifier. CMOS integrated circuits were chosen for all the identifier logic because CMOS requires little power [6]. CMOS has a disadvantage of very high input impedance, making it susceptible to any high speed voltage transients on the sensor wire pair. For the identifier power supply circuitry, tantalum and monolithic ceramic capacitors were chosen because they are small. High-frequency capacitors are important in this application to protect the CMOS logic circuitry in the identifier against fast voltage transients which must be absorbed by the identifier power supply capacitors [7]. Schottky barrier diodes were chosen for the ac voltage rectification in the identifier power supply because they have low forward voltage drops, dissipate very little power, have fast response times, and low capacitance.

One power supply design considered was a voltage doubler [8] as shown in Figure 3-1. Let V_{in} be the peak-to-peak voltage of the applied ac signal. Let V_{out} be the dc output voltage with no applied load. As V_{in} swings through its cycle, C1 charges to the negative peak voltage minus VD1.

V_{out} then becomes,

$$V_{out} = V_{in} - VD1 - VD2.$$

Therefore, the output of the doubler circuit is almost double the peak ac voltage.

The second and third designs considered were a voltage tripler and a voltage quadrupler (Figure 3-2 and Figure 3-3). As the name implies, a voltage tripler approximately triples the voltage obtained from a full wave rectifier and a quadrupler approximately quadruples this voltage. The tripler and quadrupler operate in a manner similar to the doubler.

The voltage doubler was implemented as shown as a power supply for the identifier for several reasons. The doubler has the fewer components than any other voltage multiplier circuit which is important if the final version of the supply is incorporated inside the sensor connector. The voltage doubler also has fewer diodes than the voltage tripler or quadrupler which makes a more efficient identifier power supply since diodes are the least efficient component in the proposed power supplies. Importantly, the doubler

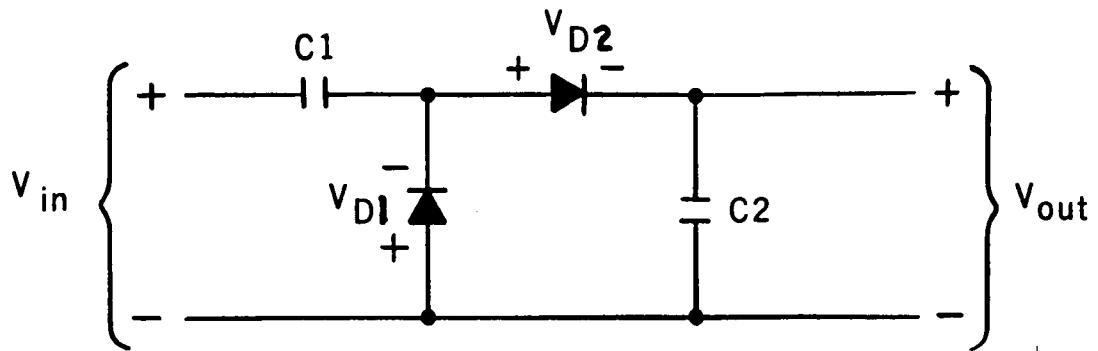


Figure 3-1. Voltage doubler.

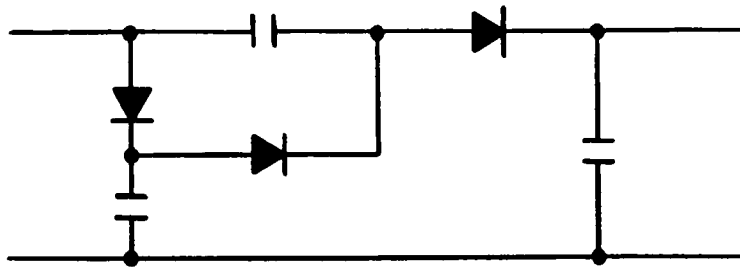


Figure 3-2. Voltage tripler.

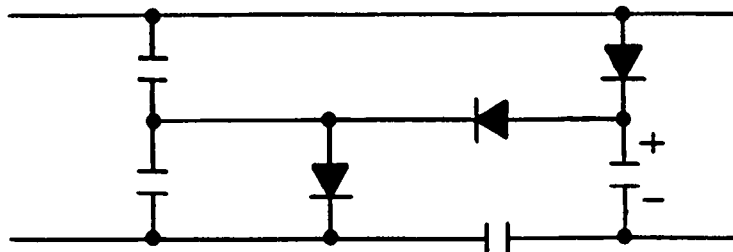


Figure 3-3. Voltage quadrupler.

develops considerably higher dc voltages from an ac signal than a half wave rectifier.

The other main consideration in the development of the power supply circuitry for the sensor identifier was the isolation of the identifier from the sensor during the identification process. A sensor could be removed from the two wire line by CMOS switches during sensor identification. Several disadvantages are involved in disconnecting the sensor from the sensor wire pair. The instrumentation normally connected to the sensor has meaningless data during the sensor identification process, therefore, this instrumentation must also be identified and its output ignored during this process. More importantly, the resistance of a CMOS switch in the "on" position is a function of temperature which could introduce errors in the transmission of information across the line. Another idea was to place an inductor in the sensor wire pair between the sensor and the sensor identifier. Since most sensor measurements are dc voltages and inductors have low resistance, the added inductor to the wire pair would affect the line dc impedance only by its resistance. Relatively low valued inductors would be a high impedance to high frequency ac voltages, but for lower frequency voltages, the physical size and value of the inductor needed to produce a high impedance would have to be much larger. For example, if the frequency of the ac voltage applied to the sensor wire pair were 50 kHz and the desired inductor impedance were $10k\Omega$,

$$Z = 2\pi f L$$

(3-1)

$$L = \frac{10 \text{ k}\Omega}{2\pi \cdot 50 \text{ kHz}} = 32 \text{ mH} . \quad (3-2)$$

A 32 mH inductor would be too large to incorporate in a sensor connector.

A notch filter in place of an inductor would also solve the problem. A notch filter would provide a high impedance to an ac voltage at a single frequency but would be almost a short circuit to dc information. A transmission zero exists at one frequency in the notch filter causing the impedance characteristics described. This has the disadvantage of allowing the identifier's ac voltage generator to operate at only the transmission zero frequency of the notch filter.

Two notch filters were considered for isolating the sensor from the identifier circuit, the twin tee (Figure 3-4) and the LC tank circuit (Figure 3-5).

The twin tee circuitry does not involve the use of inductors which tend to be large in physical size; however, it does add resistors in series with the sensor wire pair changing the dc line impedance significantly [9].

The tank circuit needs fewer components and has low resistance, therefore, it was chosen for isolating the identifier from its sensor. The inductor needed for the tank circuit may be much smaller or valued than an inductor used alone since the tank is resonant at a single frequency determined by the parallel combination of the inductor and a capacitor.

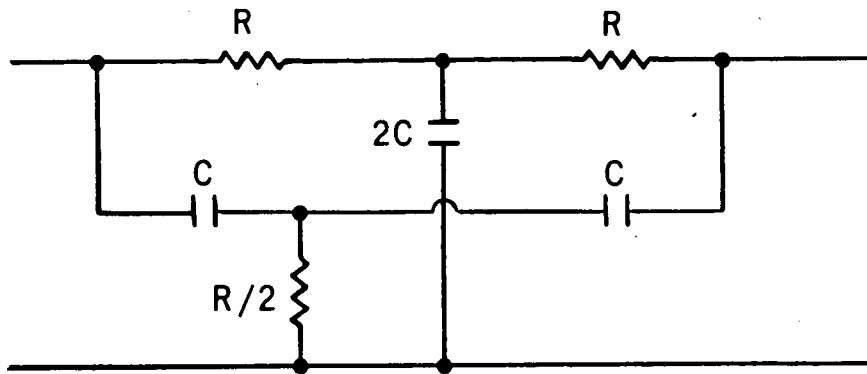


Figure 3-4. Twin tee filter.

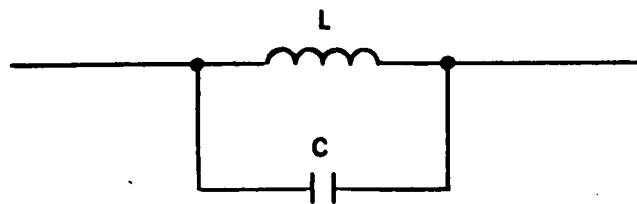


Figure 3-5. Tank filter.

The sensor identifier should work regardless of which of the two wires is chosen as identifier common. Therefore, both of the sensor wire pairs need tank circuits inserted in them between the sensor and the identifier since the sensor may be grounded; for example, in the case of a grounded junction thermocouple.

Identifier Development

Once a method of supplying dc power to the identifier circuitry was developed, a method of transmitting identifier information across the sensor wire pair was considered. If an ac voltage were used to send information across the sensor wire pair, the instrument dc voltage measurement would only be minimally by the identification process. The fixed frequency voltage identifier previously discussed operated in this manner. This identifier, however, required a separate serial line directly connected to the identifier to select the sensor to be identified. If the serial identifier and the fixed frequency identifier could be combined, a sensor identifier could be developed which only applied ac voltages to the sensor wire pair and required no serial line at the sensor for power and identification. Combination of the two identifiers could be accomplished by allowing the sensor identifier to modulate an ac voltage with a serial voltage code. Two oscillators could be used to supply the carrier ac voltage and the serial transmission frequency. The frequency of the serial transmission signal could be obtained by dividing the frequency of the ac carrier voltage so a binary counter could be used to generate the serial transmission frequency voltage rather than having two

oscillators in the system. The counter would have several advantages over an oscillator. First, the counter needs no external components (capacitors and resistors) to operate. Binary counters would also allow the serial transmission frequency to be synchronous with the ac carrier frequency. The serial transmission frequency was chosen to be $1/32$ of the carrier frequency to give sufficient separation between modulator and carrier frequencies, thereby giving confidence in the received code.

The ac voltage carrier frequency has some constraints imposed by the sensor and isolation circuitry. The carrier frequency must be the same frequency as the power generation ac voltage or a second tank circuit must be inserted in the sensor wire pair to keep a low impedance sensor from attenuating the ac carrier voltage since the tank circuitry only has one transmission zero. For all identifier ac carrier voltages to be identified, all identifiers must have nearly identical carrier voltage oscillators since frequency trim of the detector and power generation voltage would be difficult to implement for a thousand identifiers. If, however, the power generation ac voltage could be used as the carrier ac voltage, many problems would be solved. The frequency of the carrier voltage in every identifier would be identical. Power would be constantly applied to the identifier so transmitted serial words could be as long as desired and could be transmitted as often as desired. The amplitude of the carrier frequency would be determined by the instrument end of the sensor wire pair where constant dc supply voltage is available.

Since there would be constant charging of the sensor identifier, less power storage capability is needed at the identifier, allowing smaller components to be used and also causing the identifier response time to decrease. Using the power generation voltage as the carrier voltage would eliminate one oscillator with the consequent decrease in component count.

A problem which now remains is how to modulate this ac voltage carrier. Amplitude modulation (A.M.) of the carrier was chosen because few components are required and A.M. may easily be decoded with an envelope detector. A suitable scheme for a system is shown in Figure 3-6. When a wire pair is to be identified, an oscillator applies the ac carrier and power generation voltage to the sensor wire pair. The sensor identifier connected to the sensor wire pair begins to acquire dc power. After minimum voltage constraints are met, the sensor identifier's logic circuitry begins to modulate the carrier frequency with a serial voltage code by changing the ac impedance of the sensor wire pair. The ac carrier voltage is applied through impedance Z_1 at the instrument end of the sensor wire pair, the amplitude of the carrier is measured at the line side of Z_1 for demodulation. As C_1 is switched in and out, the amplitude of the ac voltage carrier at the wire pair monitor changes accordingly. Therefore, the sensor identifier circuitry does not have to drive the line, only change the sensor wire pair's impedance. If capacitors are used to change line impedance, the dc characteristics of the sensor wire pair remains unchanged.

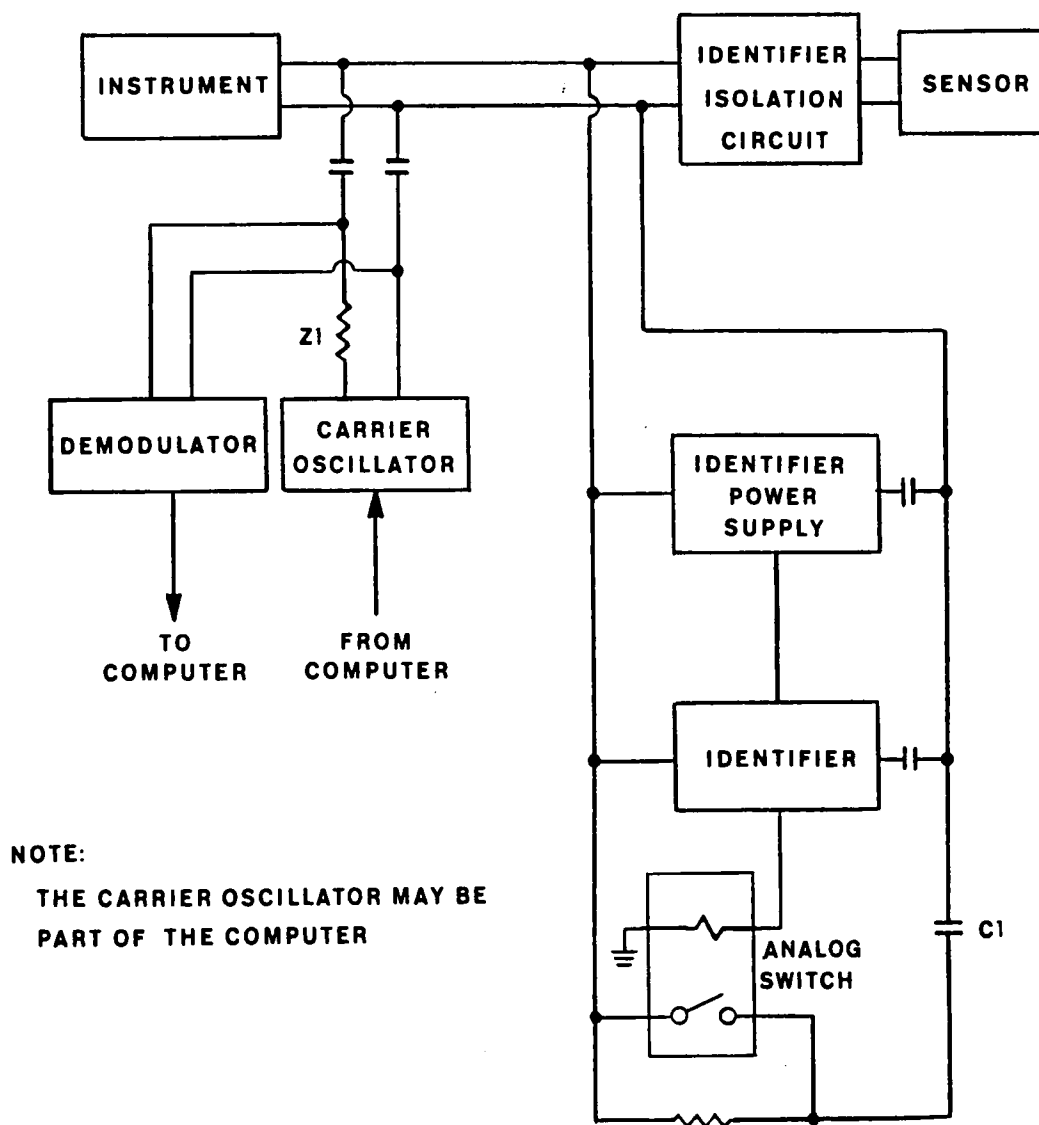


Figure 3-6. AM identifier system.

Assurance that the serial word sent was received correctly is accomplished by a continuous transmission of the serial word until the carrier voltage is removed. The detector then can compare received words to determine whether they agree. After sixteen serial bits are transmitted by the identifier, the transmission shift registers inside the serial identifier are held off and reloaded with serial information for the same amount of time taken for the serial transmission (Figure 3-7). The load/shift signal is generated by dividing the serial frequencies in the same manner as was used to generate the serial frequency. The first serial bit is high and is used as a timing set up bit for the sensor identifier circuitry insuring all bits have thirty two clock cycles. The second bit is low and is used to indicate transmission start. The other fourteen bits are used to determine what kind of sensor is used and identify exactly which one is responding. A complete detailed schematic of the described identifier is shown in Figure 3-8.

After a wire identifier has been developed, some limitations of the system should be considered. For example, what effect does changing the impedance at one end of a line have on the amplitude of the applied signal at the other end over a range of frequency? If a fixed amplitude voltage is applied at one end of the line, at what frequency will there not be enough amplitude to operate the identifier logic at the other end of the line? Problems such as these can be dealt with by developing a model of a three wire line. The next chapter, therefore, develops a model for a typical sensor line and

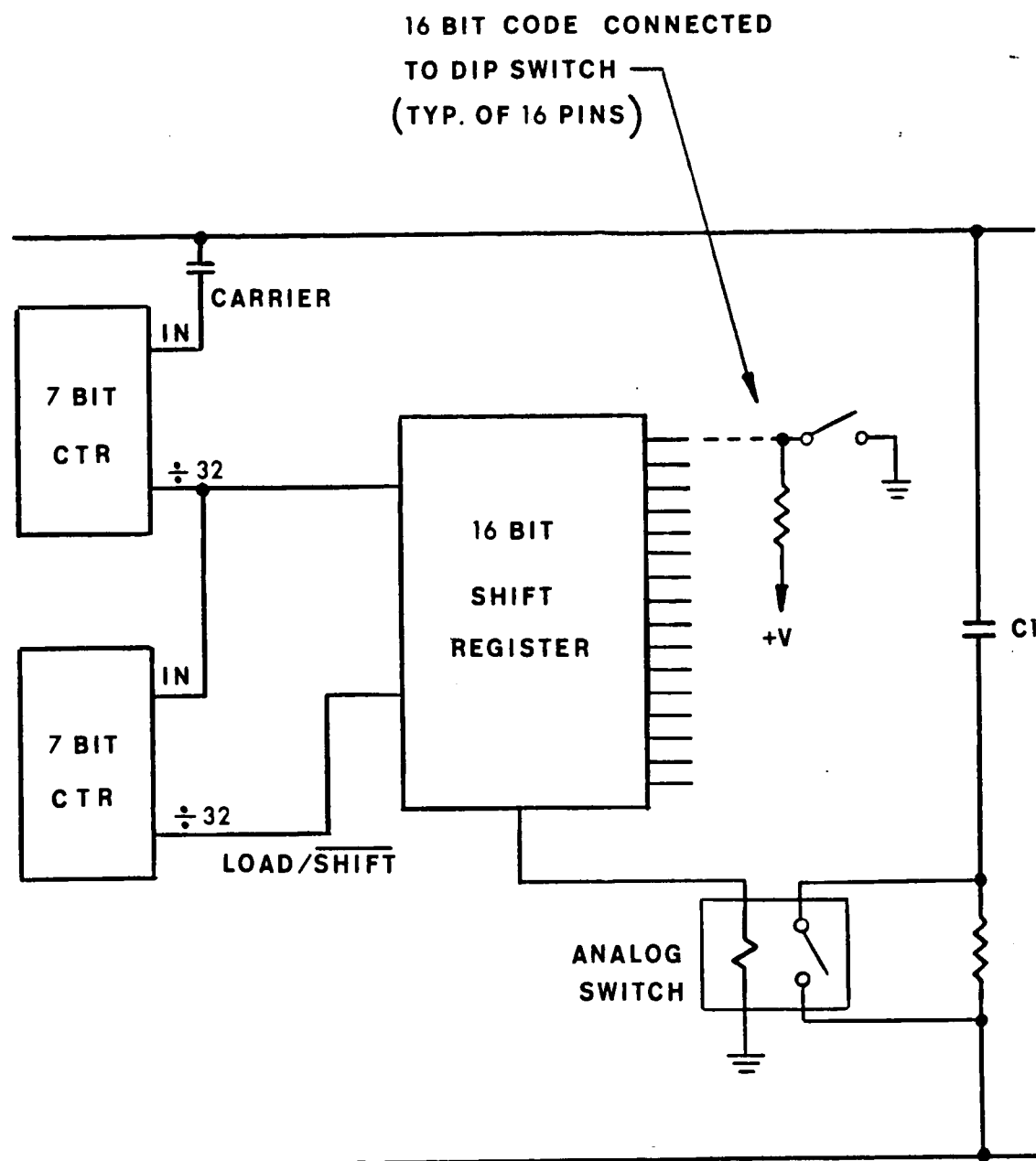


Figure 3-7. AM identifier block diagram.

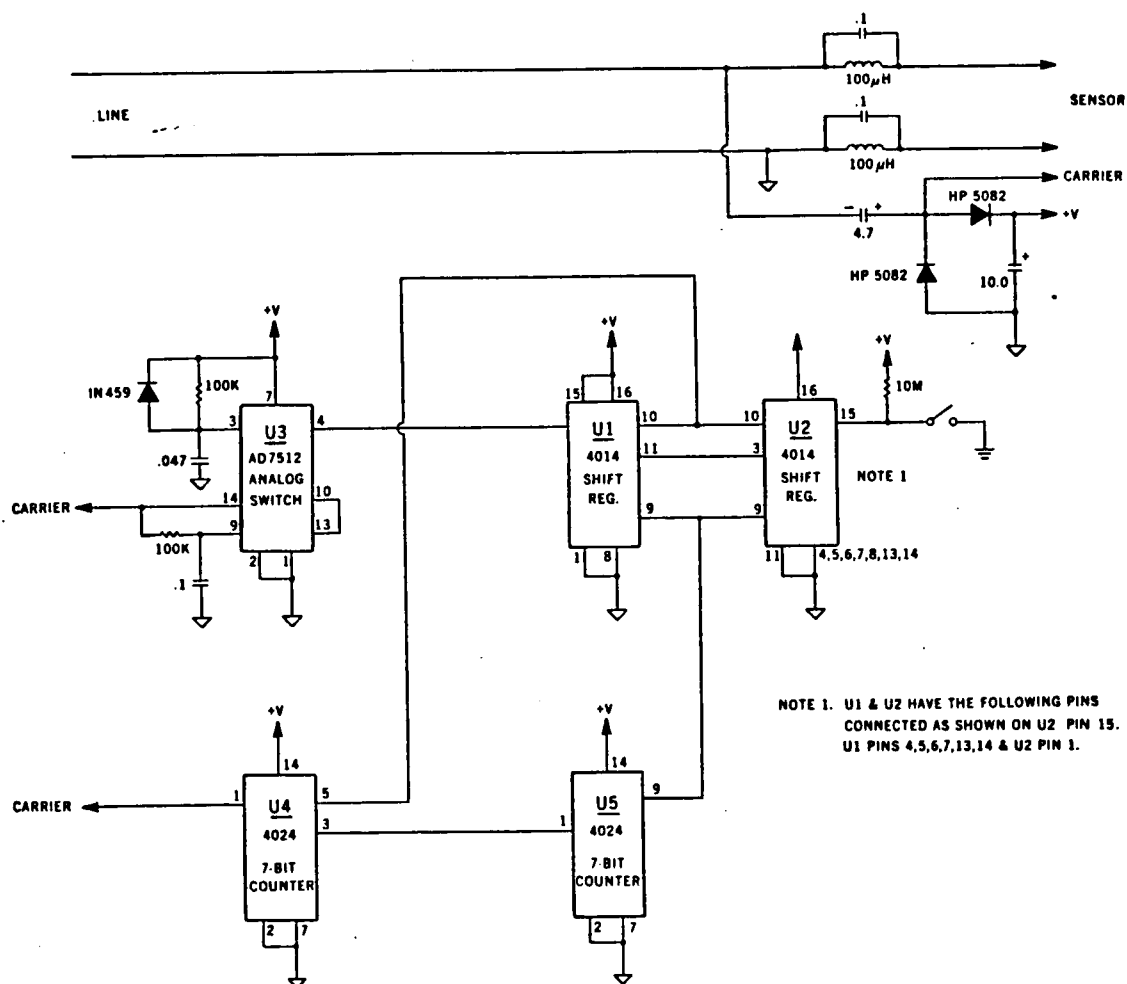


Figure 3-8. AM identifier schematic diagram.

incorporates that model into a computer program which will give the frequency limitations a line imposes on a given identifier system.

CHAPTER 4

TRANSMISSION LINE MODELING

This chapter develops a model for a typical sensor line and determines the line characteristics in a frequency range of 1 kHz to 1 MHz which is the operating range of the identifier to obtain the maximum operating frequency for specific cable characteristics. Several good reasons exist for operating the sensor identifier system near its maximum functioning frequency. The inductor and capacitor in the tank circuitry isolating the sensor from the sensor identifier can be physically smaller as the operating frequency increases. The time needed to properly identify a sensor decreases as the frequency of the ac carrier voltage increases. Also, discrimination of the sensor's DC voltage response from the identifier's carrier voltage would be easier as the frequency of the carrier increases. Modeling of a three conductor line has been developed by Dr. M. J. Roberts [10] and may easily be adapted to a model of a two wire line with a surrounding shield. The following analysis follows the work of Dr. Roberts.

Consider a small section of a two wire line with a shield. Assume voltage and current directions as shown on Figure 4-1 and then define admittance and impedance parameters for the two wire line.

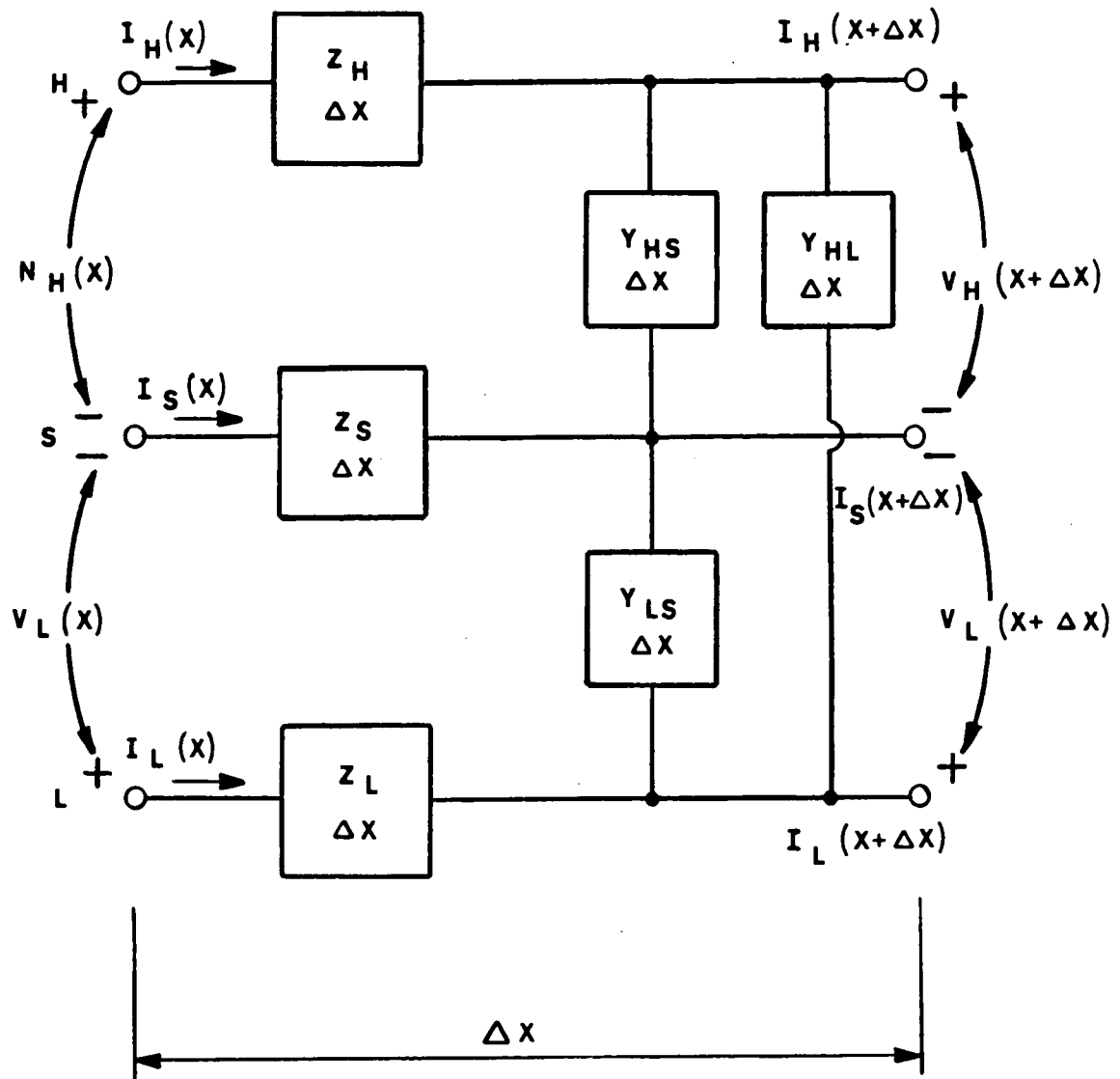


Figure 4-1. Model of a three wire line.

From the six terminal, two-port network we can easily write five equations,

$$V_H(x + \Delta x) - V_H(x) = -I_H(x)Z_H \Delta x + I_S(x) Z_S \Delta x, \quad (4-1)$$

$$V_L(x + \Delta x) - V_L(x) = -I_L(x)Z_L \Delta x + I_S(x)Z_S \Delta x, \quad (4-2)$$

$$I_H(x+\Delta x) - I_H(x) = -V_H(x + \Delta x) Y_{HS} \Delta x - [V_H(x + \Delta x) \quad (4-3)$$

$$- V_L(x + \Delta x)] Y_{HL} \Delta x,$$

$$I_L(x + \Delta x) - I_L(x) = -V_L(x + \Delta x) Y_{LS} \Delta x - [V_L(x + \Delta x) \quad (4-4)$$

$$- V_H(x + \Delta x)] Y_{HL} \Delta x, \text{ and}$$

$$\begin{aligned} I_S(x + \Delta x) - I_S(x) &= V_H(x + \Delta x) Y_{HS} \Delta x \\ &+ V_L(x + \Delta x) Y_{LS} \Delta x. \end{aligned} \quad (4-5)$$

From these five equations we find,

$$V_H(x) = \sum_{n=1}^4 A_n e^{\alpha_n x}, \quad (4-6)$$

$$V_L(x) = \sum_{n=1}^4 Q_{Bn} A_n e^{\alpha_n x}, \quad (4-7)$$

$$I_S(x) = C_I + \sum_{n=1}^4 Q_{Cn} A_n e^{\alpha_n x}, \quad (4-8)$$

$$I_H(x) = \frac{Z_S^C I}{Z_H} + \sum_{n=1}^4 Q_{Dn} A_n e^{\alpha_n x}, \text{ and} \quad (4-9)$$

$$I_L(x) = \frac{Z_S^C I}{Z_L} + \sum_{n=1}^4 Q_{En} A_n e^{\alpha_n x}. \quad (4-10)$$

where

$$Q_{Bn} = \frac{-\alpha_n^2 + K_{H1}}{K_{L2}}, \quad (4-11)$$

$$Q_{Cn} = \frac{1}{\alpha_n} \left[Y_{HS} + Y_{LS} \left(-\frac{\alpha_n^2 + K_{H1}}{K_{L2}} \right) \right], \quad (4-12)$$

$$Q_{Dn} = \frac{1}{Z_H} \left[-\alpha_n + Z_S \left\{ \frac{1}{\alpha_n} \left[Y_{HS} + Y_{LS} \left(-\frac{\alpha_n^2 + K_{H1}}{K_{L2}} \right) \right] \right\} \right], \quad (4-13)$$

$$Q_{En} = \frac{1}{Z_L} \left[-\alpha_n \left(-\frac{\alpha_n^2 + K_{H1}}{K_{L2}} \right) + Z_S \left\{ \frac{1}{\alpha_n} \left[Y_{HS} + Y_{LS} \left(-\frac{\alpha_n^2 + K_{H1}}{K_{H2}} \right) \right] \right\} \right], \quad (4-14)$$

and

$$K_{H1} = -Z_H (Y_{HS} + Y_{HL}) - Z_S Y_{HS} , \quad (4-15)$$

$$K_{L2} = Z_H Y_{HL} - Z_S Y_{LS} , \quad (4-16)$$

$$K_{L1} = -Z_L (Y_{LS} + Y_{HL}) - Z_S Y_{LS} , \quad (4-17)$$

$$K_{H2} = Z_L Y_{HL} - Z_S Y_{HS} , \quad (4-18)$$

$$\text{COEF1} = K_{L1} + K_{H1} , \quad (4-19)$$

$$\text{COEF2} = K_{L1} K_{H1} - K_{H2} K_{L2} , \text{ and} \quad (4-20)$$

$$\alpha_n = \pm \sqrt{-\frac{\text{COEF1}}{2} \pm \sqrt{\frac{(\text{COEF1})^2}{4} - \text{COEF2}}} . \quad (4-21)$$

A complete derivation may be found in Appendix A.

For the case 1 where the shield is ungrounded (Figure 4-2) we know

$$I_H(0) + I_L(0) = 0 , \quad (4-22)$$

$$I_S(0) = 0 , \quad (4-23)$$

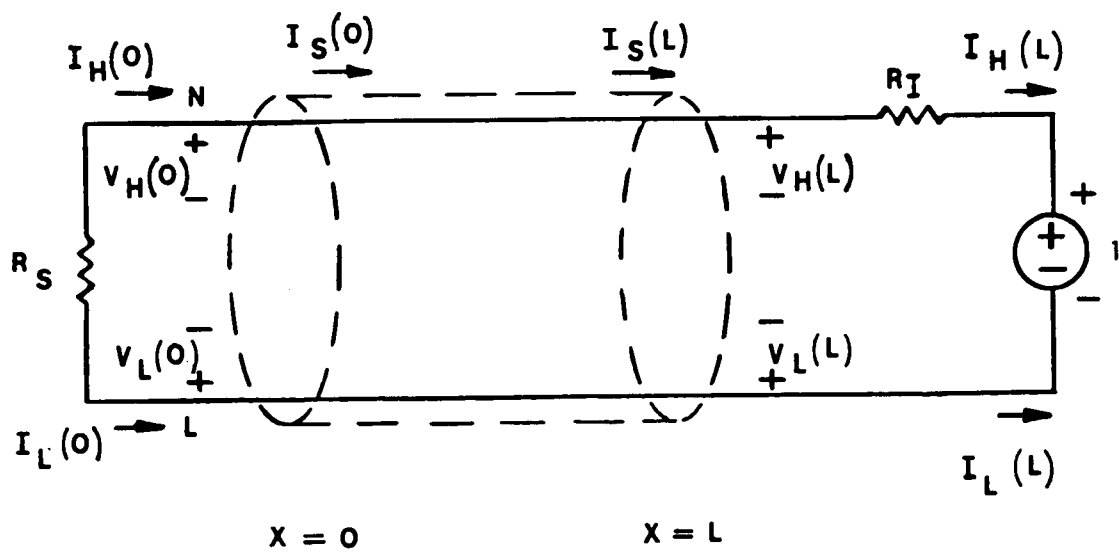


Figure 4-2. Model of three wire line with shield ungrounded.

$$V_H(0) - V_L(0) - [I_L(0)] R_S = 0 , \quad (4-24)$$

$$V_H(L) - V_L(L) - R_I I_H(L) = 1 , \text{ and} \quad (4-25)$$

$$I_H(L) + I_L(L) = 0 . \quad (4-26)$$

From (4-9), (4-10), and (4-22)

$$\frac{Z_S^C I}{Z_H} + \sum_{n=1}^4 Q_{Dn} A_n + \frac{Z_S^C I}{Z_L} + \sum_{n=1}^4 Q_{En} A_n = 0 . \quad (4-27)$$

From (4-8) and (4-23)

$$C_I + \sum_{n=1}^4 Q_{Cn} A_n = 0 . \quad (4-28)$$

From (4-6), (4-7), (4-10) and (4-24)

$$\sum_{n=1}^4 A_n - \sum_{n=1}^4 Q_{Bn} A_n - \left[\frac{Z_S^C I}{Z_L} + \sum_{n=1}^4 Q_{En} A_n \right] R_S = 0 . \quad (4-29)$$

From (4-6), (4-7), (4-9), and (4-25)

$$\sum_{n=1}^4 A_n e^{\alpha_n L} - \sum_{n=1}^4 Q_{Bn} A_n e^{\alpha_n L} - R_I \left[\frac{Z_S^C I}{Z_H} + \sum_{n=1}^4 Q_{Dn} A_n e^{\alpha_n L} \right] = 1 . \quad (4-30)$$

From (4-9), (4-10), and (4-26),

$$\frac{Z_S C_I}{Z_H} + \sum_{n=1}^4 Q_{Dn} A_n e^{\alpha_n L} + \frac{Z_S C_I}{Z_L} + \sum_{n=1}^4 Q_{En} A_n e^{\alpha_n L} = 0. \quad (4-31)$$

$\begin{bmatrix} (Q_{D1}+Q_{E1}) (Q_{D2}+Q_{E2}) (Q_{D3}+Q_{E3}) (Q_{D4}+Q_{E4}) \frac{Z_S}{Z_H} + \frac{Z_S}{Z_L} \\ \\ Q_{C1} & Q_{C2} & Q_{C3} & Q_{C4} & 1 \\ \\ (1-Q_{B1}-Q_{E1}R_S) (1-Q_{B2}-Q_{E2}R_S) (1-Q_{B3}-Q_{E3}R_S) (1-Q_{B4}-Q_{E4}R_S) \\ \\ - \frac{Z_S R_S}{Z_L} \\ \\ e^{\alpha_1 L} (1-Q_{B1}-R_I Q_{D1}) e^{\alpha_2 L} (1-Q_{B2}-R_I Q_{D2}) e^{\alpha_3 L} (1-Q_{B3}-R_I Q_{D2}) \\ \\ e^{\alpha_3 L} (1-Q_{B4}-R_I Q_{D4}) \frac{R_I Z_S}{Z_H} \\ \\ e^{\alpha_1 L} (Q_{D1}+Q_{E1}) e^{\alpha_2 L} (Q_{D2}+Q_{E2}) e^{\alpha_3 L} (Q_{D3}+Q_{E3}) e^{\alpha_4 L} (Q_{D4}+Q_{E4}) \frac{Z_S}{Z_H} + \frac{Z_S}{Z_L} \end{bmatrix}$	<table border="1" style="width: 100%; border-collapse: collapse;"> <tr><td style="text-align: center; padding: 5px;">A_1</td><td style="text-align: center; padding: 5px;">0</td></tr> <tr><td style="text-align: center; padding: 5px;">A_2</td><td style="text-align: center; padding: 5px;">0</td></tr> <tr><td style="text-align: center; padding: 5px;">A_3</td><td style="text-align: center; padding: 5px;">0</td></tr> <tr><td style="text-align: center; padding: 5px;">A_4</td><td style="text-align: center; padding: 5px;">1</td></tr> <tr><td style="text-align: center; padding: 5px;">C_I</td><td style="text-align: center; padding: 5px;">0</td></tr> </table>	A_1	0	A_2	0	A_3	0	A_4	1	C_I	0
A_1	0										
A_2	0										
A_3	0										
A_4	1										
C_I	0										

Case 2 where shield is grounded at the instrument (Figure 4-3)

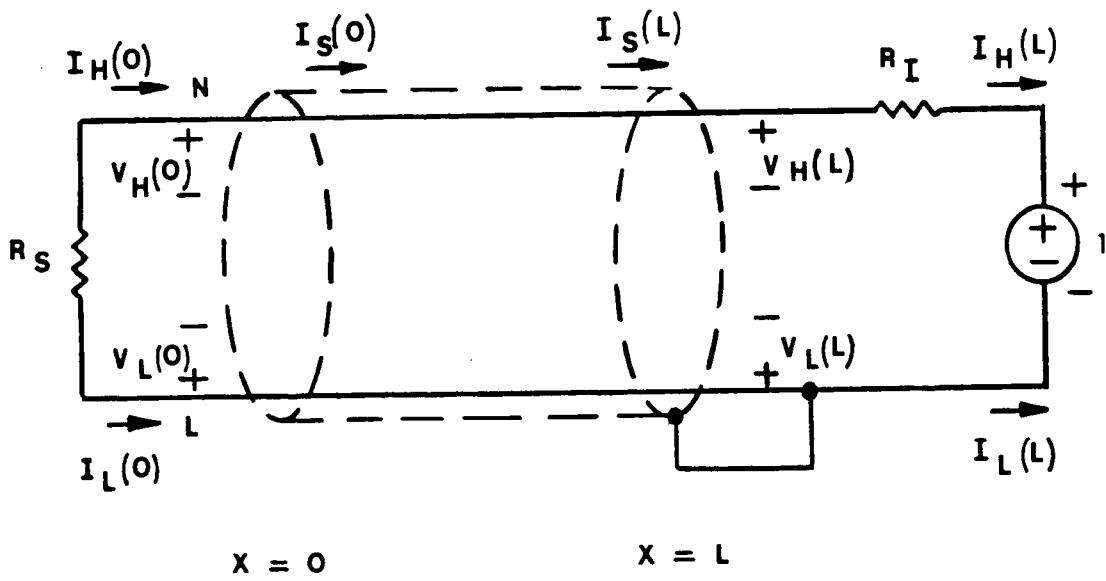


Figure 4-3. Three wire line model with shield grounded at one end.

$$I_H(0) + I_L(0) = 0 , \quad (4-32)$$

$$I_S(0) = 0 , \quad (4-33)$$

$$V_H(0) - V_L(0) - R_S I_L(0) = 0 , \quad (4-34)$$

$$V_H(L) - I_H(L) R_I = 1 , \text{ and} \quad (4-35)$$

$$V_L(L) = 0 . \quad (4-36)$$

The first three equations for this case are the same as Case 1

From (4-6), (4-9), and (4-35),

$$\sum_{n=1}^4 A_n e^{\alpha_n L} - R_I \frac{Z_S^C I}{Z_H} + \sum_{n=1}^4 Q_{Dn} A_n e^{\alpha_n L} = 1 . \quad (4-37)$$

from (4-7) and (4-36)

$$\sum_{n=1}^4 Q_{Bn} A_n e^{\alpha_n L} = 0 . \quad (4-38)$$

$$\begin{bmatrix}
 (Q_{D1}+Q_{E1}) & (Q_{D2}+Q_{E2}) & (Q_{D3}+Q_{E3}) & (Q_{E4}+Q_{E4}) & \frac{Z_S}{Z_H} + \frac{Z_S}{Z_L} \\
 Q_{C1} & Q_{C2} & Q_{C3} & Q_{C4} & 1 \\
 (1-Q_{B1}-R_S Q_{E1}) & (1-Q_{B2}-R_S Q_{E2}) & (1-Q_{B3}-R_S Q_{E3}) & (1-Q_{B4}-R_S Q_{E4}) & \frac{Z_S^R}{Z} \\
 e^{\alpha_1^L (1-R_I Q_{D1})} & e^{\alpha_2^L (1-R_I Q_{D2})} & e^{\alpha_3^L (1-R_I Q_{D3})} & e^{\alpha_4^L (1-R_S Q_{D4})} & \frac{Z_S^R}{Z_H} \\
 e^{\alpha_1^L (Q_{B1})} & e^{\alpha_2^L (Q_{B2})} & e^{\alpha_3^L (Q_{B3})} & e^{\alpha_4^L (Q_{B4})} & 0
 \end{bmatrix}
 \begin{bmatrix}
 A_1 \\
 A_2 \\
 A_3 \\
 A_4 \\
 C_I
 \end{bmatrix}
 =
 \begin{bmatrix}
 0 \\
 0 \\
 0 \\
 1 \\
 0
 \end{bmatrix}$$

The elements of the matrices derived for the two cases above were incorporated into a Flecs [11] computer program. This program allows the user to enter impedance parameters for a three wire line, allowable voltage amplitude tolerances on a sensor identifier system, and other pertinent data (i.e., line length). The program also accepts a value for permeability and accounts for the resistance changes due to skin effect. The program calculates an allowable operating carrier frequency range for the identifier imposed by the line. The program was derived from a program developed by M. J. Roberts [10] for modeling a three wire line and is included in its entirety in Appendix B.

Testing of this model with various length cables will be discussed in the next chapter with reports all experimental testing of the identifier.

CHAPTER 5

EXPERIMENTAL RESULTS

This chapter presents the results of tests made on the prototype identifier of Chapter 3 and verifies the line effects calculated in Chapter 4.

A functionality test was first performed on the sensor identifier system. A method of exciting the identifier and decoding its transmitted signal must be developed to show a sensor identifier will operate properly. Decoding the signal requires first that identifier signal is demodulated and converted into TTL logic levels, and secondly that these logic levels are converted into displayed information about the sensor. The interface circuitry consists of the line exciter and demodulator and the computer monitor converts the logic code into displayed information.

The identifier interface consists of an oscillator for generating the carrier excitation voltage and a monitor to measure the line modulation and generate serial voltage codes. Demodulation is accomplished by receiving the ac carrier voltage into a half wave rectifier, then low-pass filtering the rectified signal. The result is a sequence of pulses which are then applied to a voltage comparator where they are converted to TTL voltage logic levels (Figure 5-1).

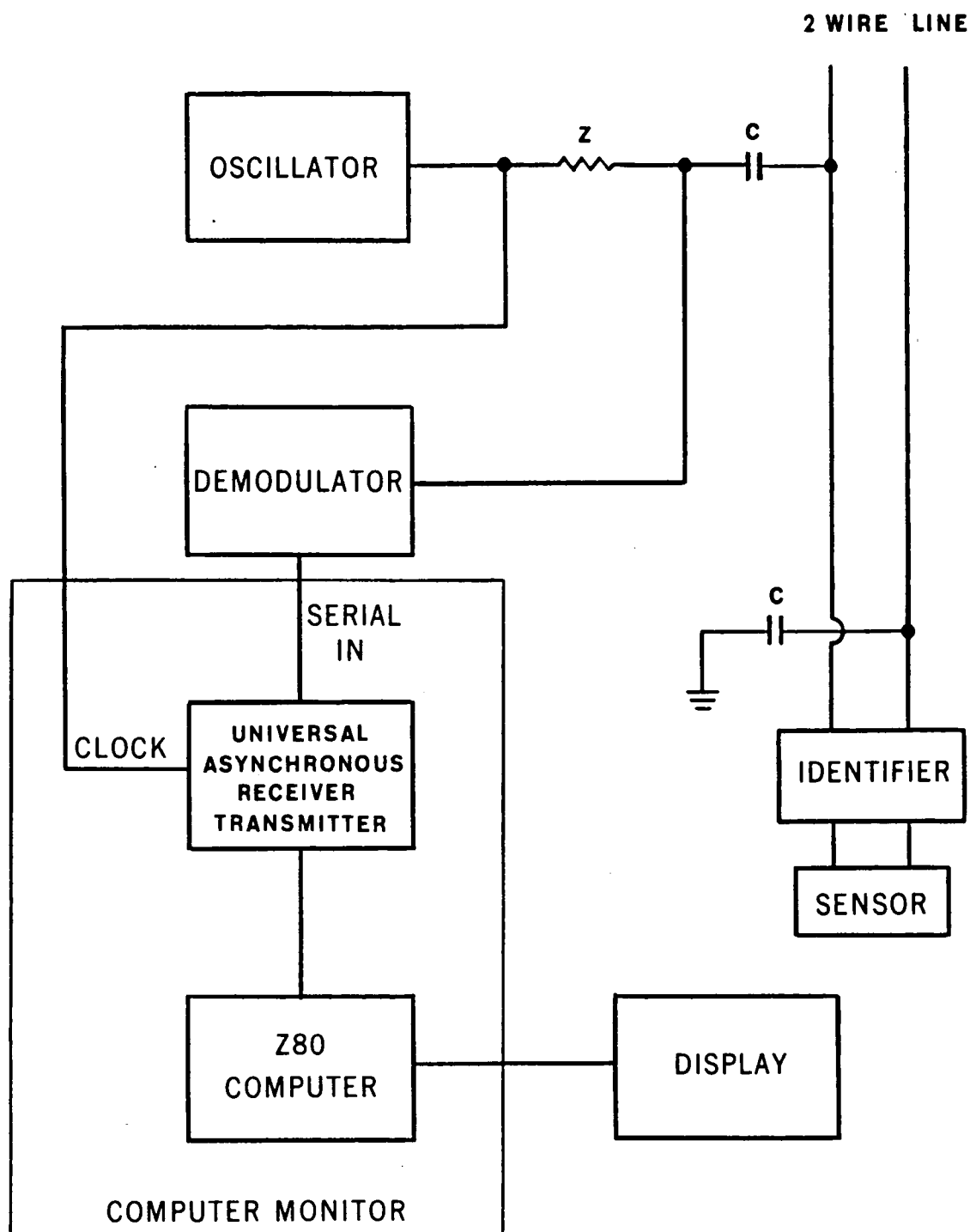


Figure 5-1. Identifier interface.

The computer monitor receives the serial information from the interface circuitry in TTL format into a universal asynchronous receiver transmitter (UART). The serial word is then decoded to determine which sensor is being identified. Once three successive readings agree, the serial word is assumed to be valid. If no start bit is received after a time out period set in the computer, the sensor wire pair is assumed to be defective and the display indicates no line. After the information sent from an identifier is decoded, it is displayed. The prototype sensor identifiers have dip switches allowing any code to be set in any identifier. The computer chosen for simulation was an STD bus single board Z80 microprocessor-based computer. This computer had the needed serial interface available and was physically small. A display was connected directly to the computer's address and data bus as part of its memory map. Information about a sensor wire pair could be displayed simply by writing ASCII values to a input/output location. A schematic of the designed system is shown in Figure 5-2.

The sensor identifier described in Chapter 3, which amplitude modulates the excitation voltage by changing the line impedance, was built along with the line exciter, demodulator, and a decoder. The exciter has an output voltage of 15 V peak-to-peak and its frequency can be easily varied for different applications. A 15 V amplitude of the excitation was chosen for testing the prototype identifier because it is easily generated. This voltage may be too high for

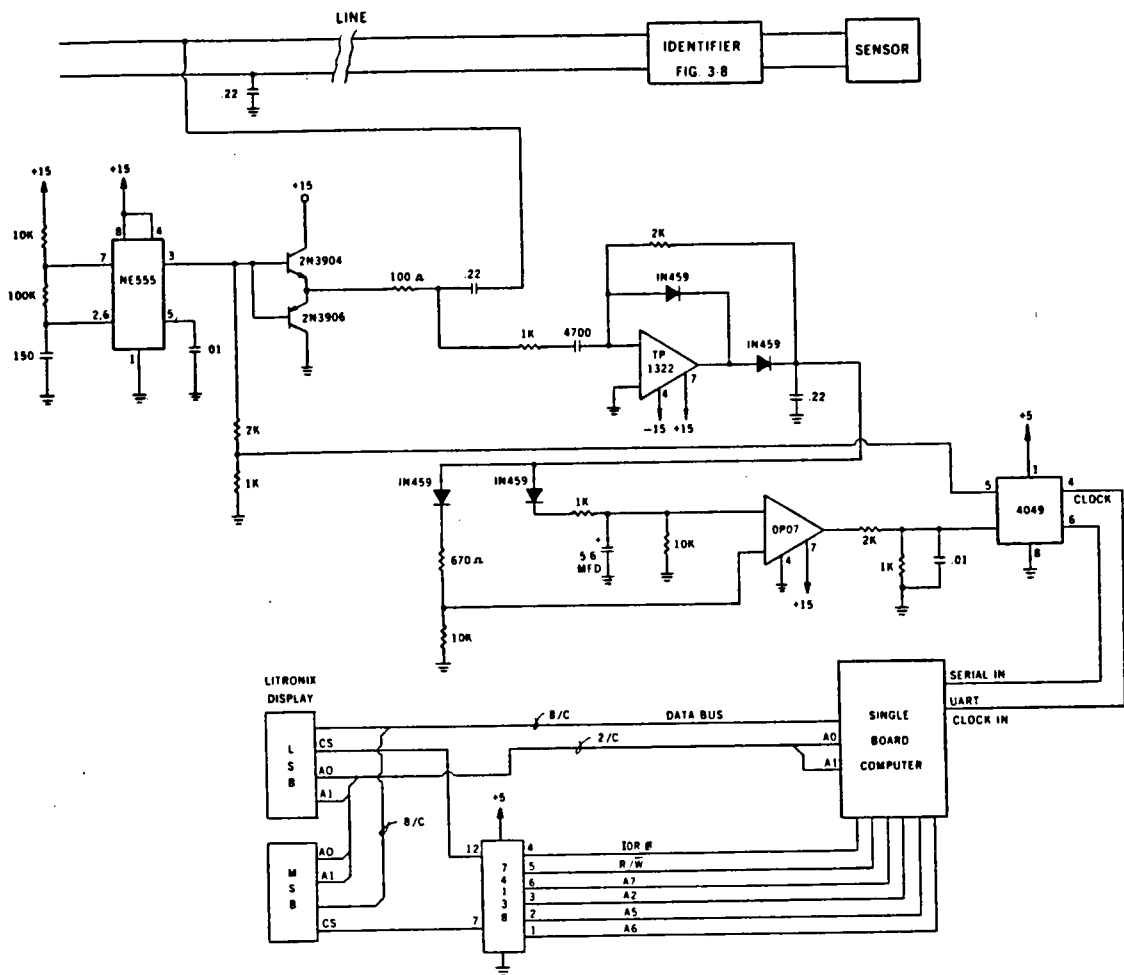


Figure 5-2. AM identifier system schematic diagram.

general use in an identifier system but should not damage the thermocouple instrumentation chosen for the proof of the identifiers operation. The demodulator and TTL converter developed for the prototype unit assumes the normal state of the modulation of the excitation voltage is a logic high. Therefore, if no identifier is connected to the line, the output of the TTL converter is high (+5 V). Future designs might incorporate a decoder which would allow the normal state of the line to be either high or low. The initial test frequency for the wire identifier was 10 kHz. This frequency was chosen mainly to allow an identification to be made quickly since the serial transmission rate is a multiple of the excitation frequency. Secondly, the higher the excitation frequency, the easier it is to isolate from connected sensor instrumentation. Thirdly, the modeling in Chapter 4 indicates this frequency should be adequate for short lengths of line. The tank circuitry used to isolate the sensor from the sensor identifier was tuned to the excitation frequency (f_r) by selecting an inductor (100 μ H) and solving the following equation for capacitance;

where

$$C = 1/(4 \pi^2 f_r^2 L) .$$

An oscilloscope was connected across the line to monitor the modulation of the excitation voltage by the identifier. A one foot

line without a sensor connected was chosen for the initial testing of the identifier system. Power was applied to the system and the decoder responded with the proper identification code. A 0.1 V modulation voltage is needed to overcome hysteresis designed into the decoder used for the prototype unit. The modulated serial code was observed by monitoring the excitation voltage with an oscilloscope (Figure 5-3). The line was then shorted at the sensor end to determine if the identifier would operate properly for a low impedance sensor. Power was then applied to the identification system and the computer responded with the proper identification code. Figure 5-4 shows the oscilloscope trace of the voltage on the line. A repeat of the above tests was performed with an excitation frequency of 4 kHz to determine if the identifier could operate at a different frequency. Identifications were correctly made.

After the identifier initial functionality was confirmed, a test to determine if the identifier could transmit its digital code along a line was performed. A two hundred foot line replaced the one foot line of the previous setup and the above tests were repeated. The identifier modulated the excitation voltage correctly and the decoder displayed the proper code. The identifier code was varied by changing the position of the dip switches shown in Figure 3-7, page 27, and the identifier system correctly identified each new code.

A test of how the identifier reacts to a very long line was made. A 5000 foot line replaced the two hundred foot line of the

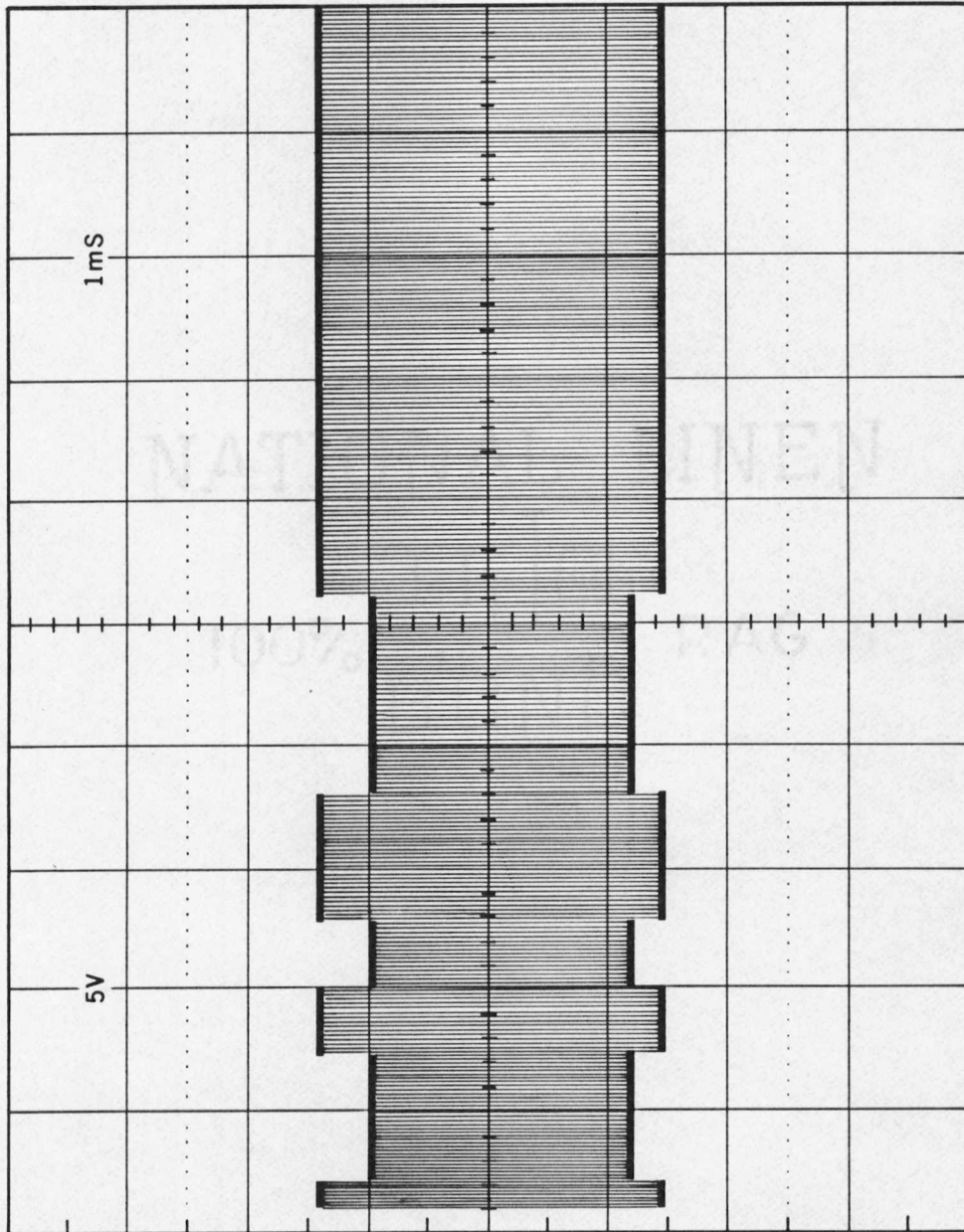


Figure 5-3. AM modulation on unterminated line.

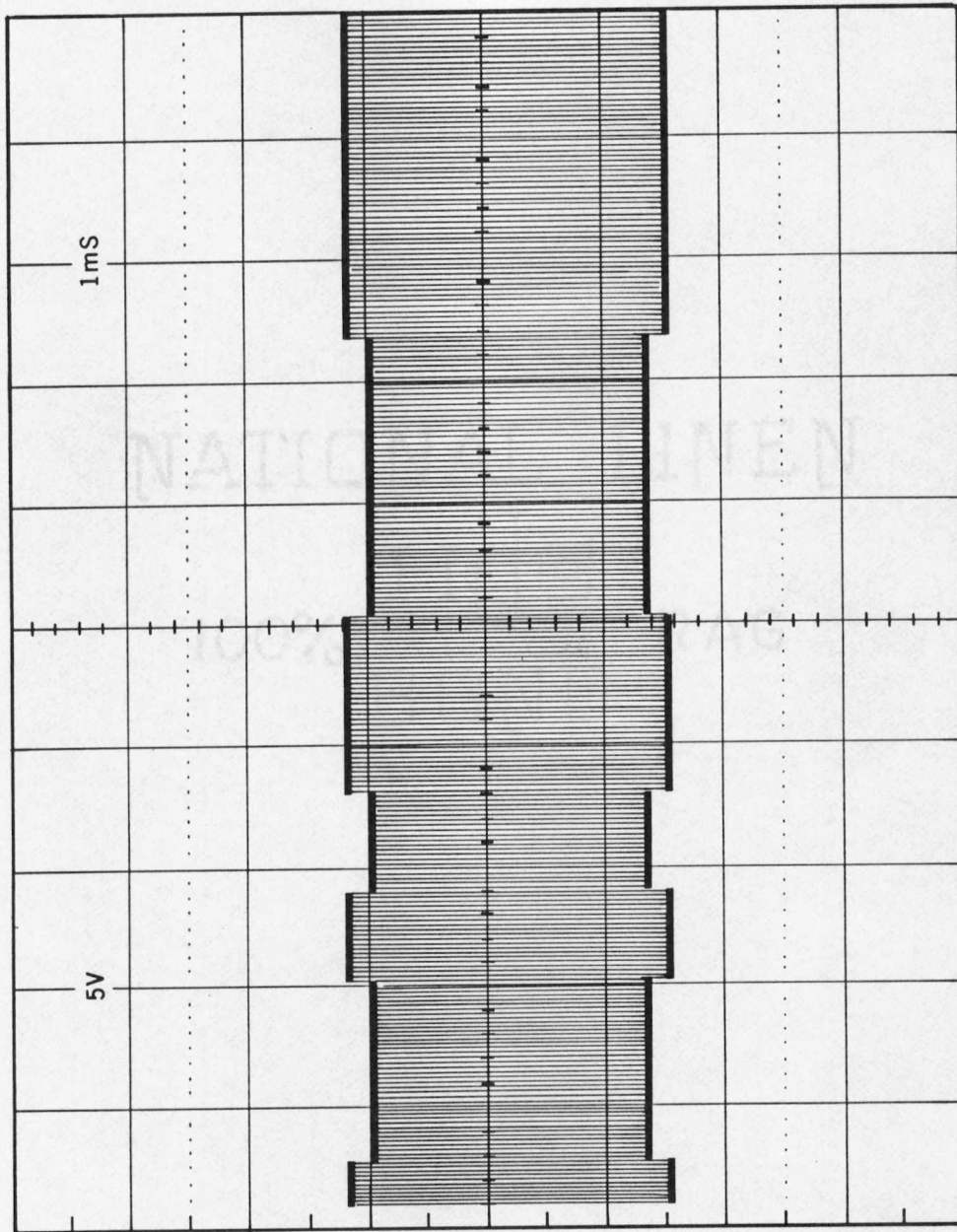


Figure 5-4. AM modulation on line terminated in a short.

previous setup. Power was applied and the line was excited with a 15 V, 10 kHz square wave. Modulation on the line was observable on the oscilloscope but undetected by the demodulator. The modulation on the line was inverted from the previous tests indicating the line impedance was increasing as the identifier applied resistance across the line decreased (Figure 3-7, page 27). Since the demodulator used assumes the initial state of the line is high, no detection was made of this inverted signal. The inversion of the modulation agrees with the results of modeling the line in Chapter 4 which indicates a frequency range for each line checked in which shorting one end of a line could increase the magnitude of the input impedance seen from the other end of the line. In an effort to observe how the identifier responds to different applied excitation frequencies, the frequency of excitation voltage applied to the 5000 foot cable was varied. With an excitation frequency of 50 kHz, no modulation of the excitation voltage could be observed with an oscilloscope. With a frequency of 1 kHz, the identifier operated normally.

After testing the identifier with various length cables and at various carrier frequencies, a test was designed to verify that the identifier system operated normally when it was incorporated into an existing thermocouple system. The thermocouple system incorporated a thermocouple voltage to temperature readout instrument with 0.1 degree Fahrenheit resolution (Doric Trendicator) with a type K thermocouple. The instrument was borrowed and could not be

recalibrated for the thermocouple used so there is some offset error in the obtained readings. Two major questions must be answered to determine if the identifier system can be incorporated successfully into a thermocouple system. First, how is the temperature of the thermocouple system affected when the identifier is connected and second, will the identifier operate normally connected to the thermocouple system? A one foot line was initially connected in the thermocouple system without an identifier to obtain a reading of the normal operation of the thermocouple instrumentation. A thermocouple was connected to the line and the thermocouple system gave a reading of 76.2 degrees Fahrenheit with the thermocouple at ambient temperature. The thermocouple was then immersed in a mixture of ice and water and the uncalibrated thermocouple system gave a reading of 36.3 degrees Fahrenheit. The identifier system was then incorporated into the thermocouple system as shown in Figure 5-5. Power was applied to the thermocouple system only and a reading of 36.2 degrees Fahrenheit was taken. Since the difference in the reading is equal to the resolution of the instrument, it is hard to quantify. The possible error incurred could be as much as 0.5%. This error could be caused from several different sources. The thermocouple instrumentation has pull up resistors connected to its input amplifier to detect breaks in the attached thermocouple line (Figure 5-6). These resistors cause a small dc current to be flowing in the thermocouple line at all times. The inductors in the identifier isolator circuit have resistances.

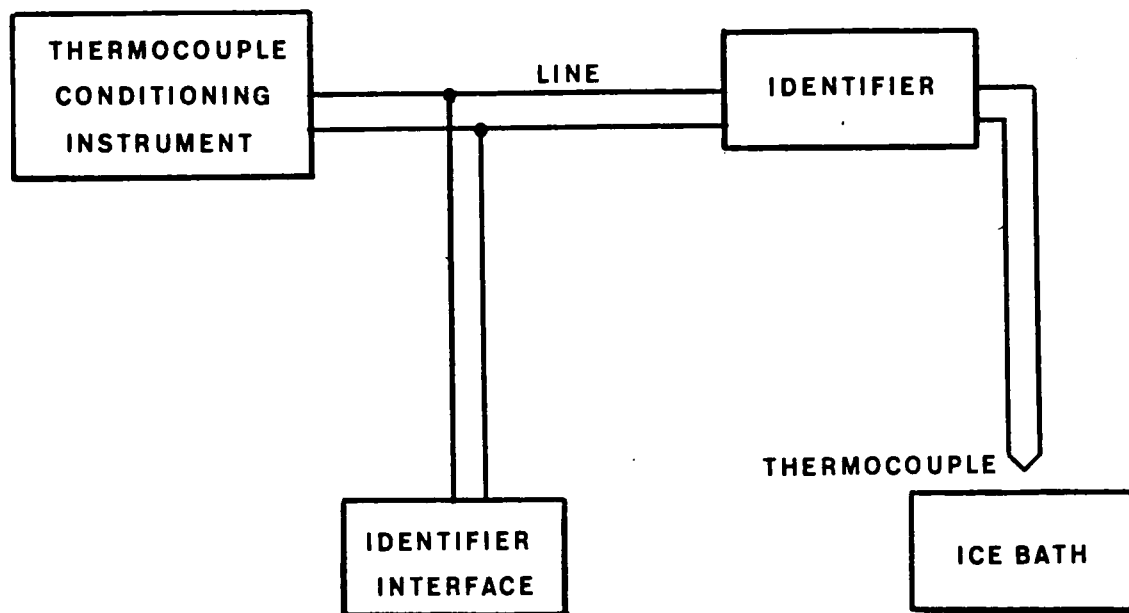


Figure 5-5. AM identifier incorporated into a thermocouple system.

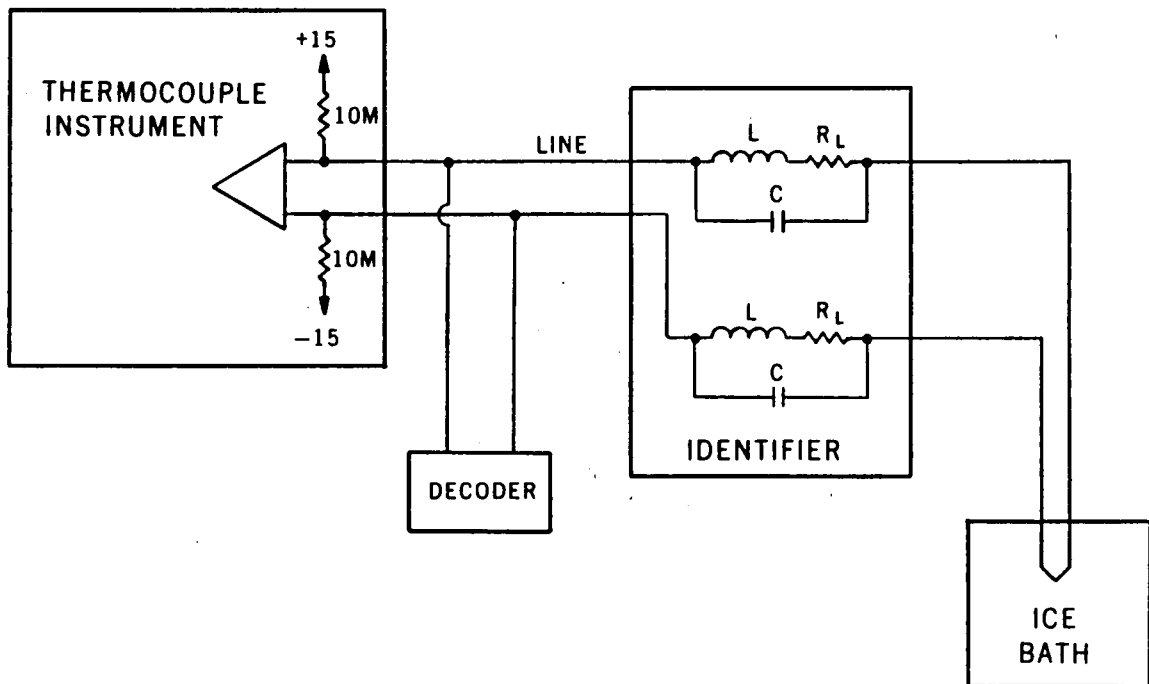


Figure 5-6. Pull up resistors in thermocouple instrumentation.

Therefore, any voltages developed across these inductors due to the dc current in the line would cause an error in the temperature measurement. The 0.5% error in the temperature measurement could also be caused by temperature differences in the test wiring which connects the wire identifier into the thermocouple system causing some thermoelectric potentials to be generated across the line. The line length was increased to 75 feet and a temperature measurement was made with the same measured results. This test was repeated again with 150 feet of cable with the same measured results. These tests indicate that incorporating the identifier system into this thermocouple system with reasonable line lengths has little effect on the temperature measurement.

With the above setup and a one foot line, a test of the functionality of the identifier system was performed. The identifier correctly modulated the excitation voltage and displayed the correct code. The temperature measurement gave fluctuating results during the identification process because the applied excitation voltage interfered with the temperature measurement, but returned to a correct reading when identification was discontinued. Incorporating tank circuits between the decoder connection to the line and the thermocouple instrumentation should eliminate most of the reading fluctuations. The identifier functionality tests were repeated with 75 and 150 feet cables with the thermocouple being properly identified.

A type K thermocouple cable with a braided ribbon stainless steel sheath and a type K thermocouple with a solid stainless steel sheath were selected to verify the wire model developed in Chapter 4. The line impedance of each of these cables was measured by connecting each cable onto a HP 4192A LF impedance analyzer, loading the cable with a resistance whose magnitude was an approximation of the identifier's impedance, and measuring the input impedance phase and magnitude of the cable over a given frequency range. An approximation of the ac impedance of the wire identifier between 5 kHz and 1 MHz was made by monitoring the line modulation during the identification process and calculated the resistance needed to simulate and identifier in each of its modes of operation. The high impedance mode has an impedance magnitude of approximately 750 ohms in the above frequency range. The low impedance mode has an impedance magnitude of approximately 470 ohms.

The results of the impedance measurements for a 252 foot, braided stainless steel sheath, type K thermocouple cable are shown in Figures 5-7 through 5-10. The results of the impedance measurements for a 32 foot, solid stainless steel sheath, type K thermocouple cable are shown in Figures 5-9 through 5-14.

Based on the measured line impedances, values for the line impedance parameters were generated for the computer model of Chapter 4. These parameters are listed in Table 5-1. To determine the operating frequency range allowable for the carrier frequency of

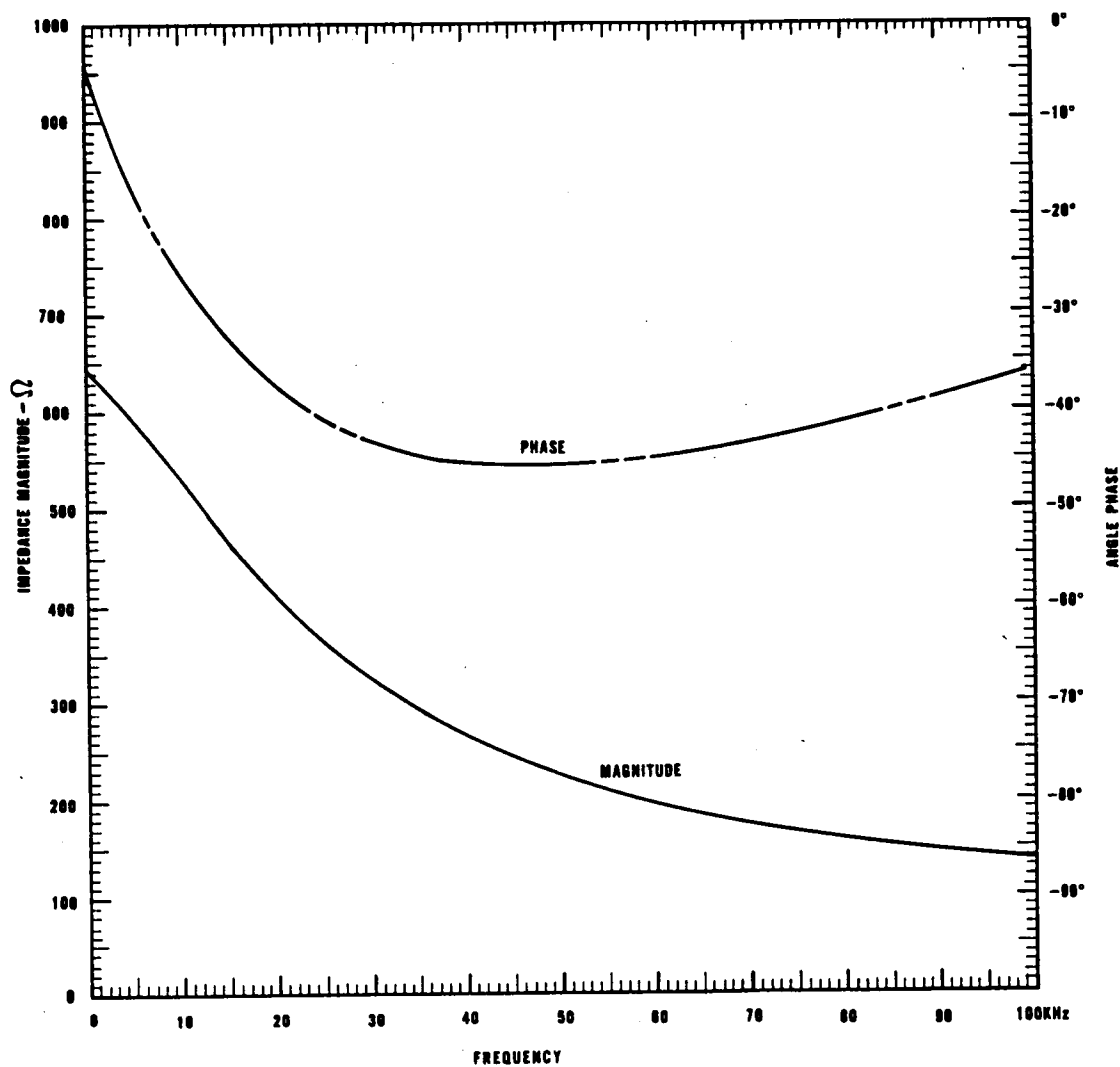


Figure 5-7. Line impedance of a 252 ft braided sheath type K thermocouple cable with a load of 470 ohms and the sheath ungrounded.

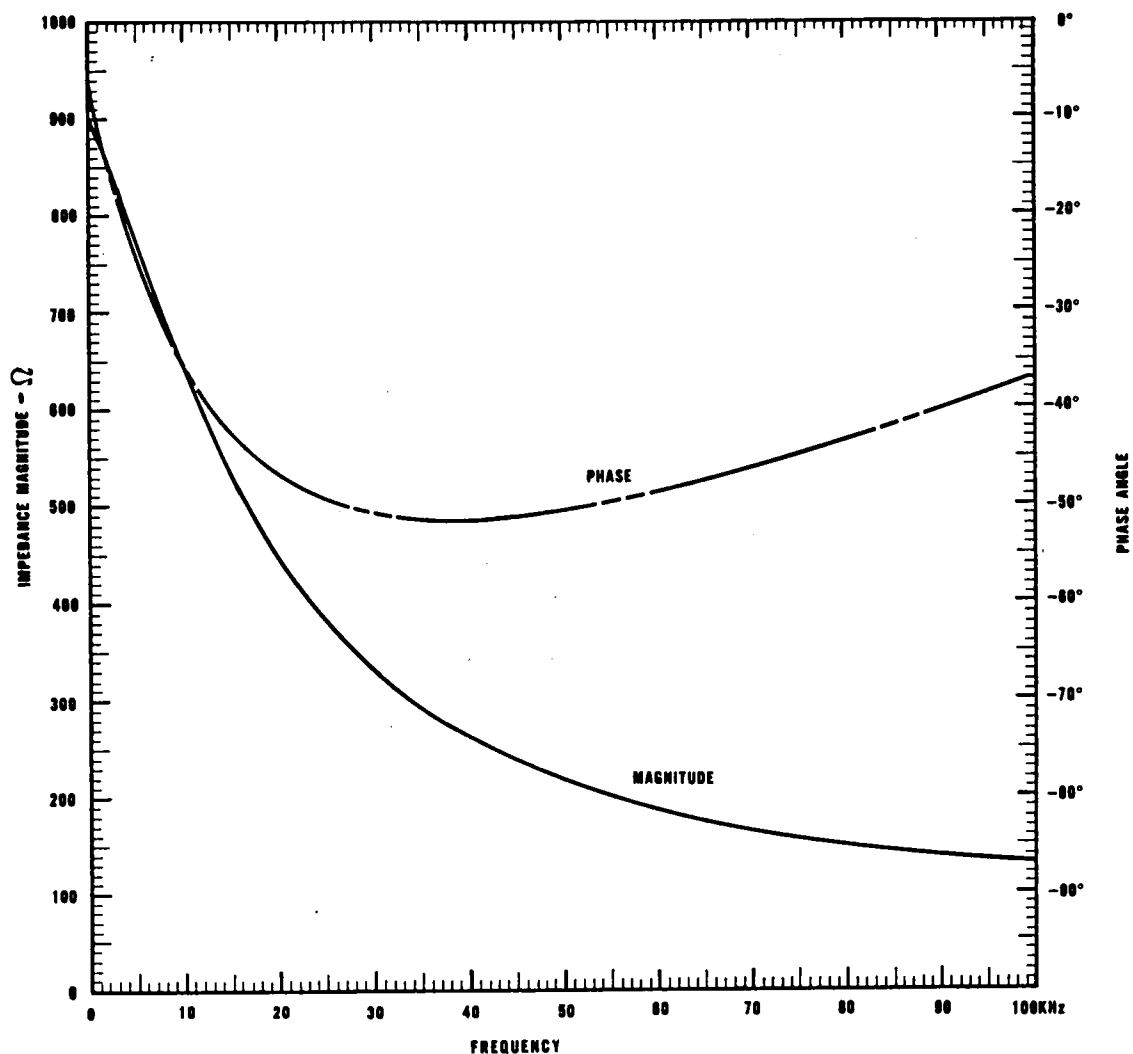


Figure 5-8. Line impedance of a 252 ft braided sheath type K thermocouple cable with a load of 750 ohms and the sheath ungrounded.

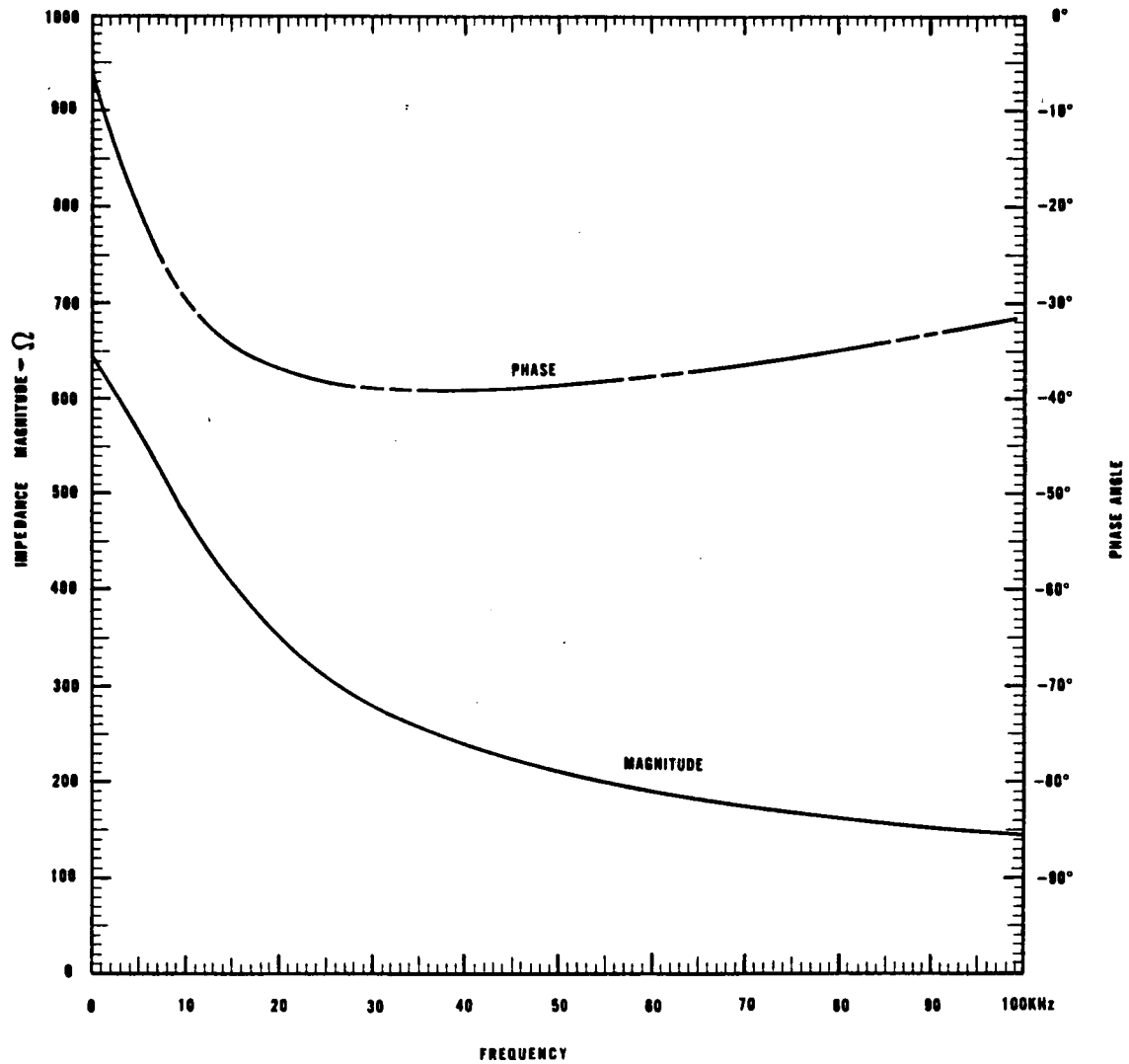


Figure 5-9. Line impedance of a 252 ft braided sheath type K thermocouple cable with a load of 470 ohms grounded at receiving end.

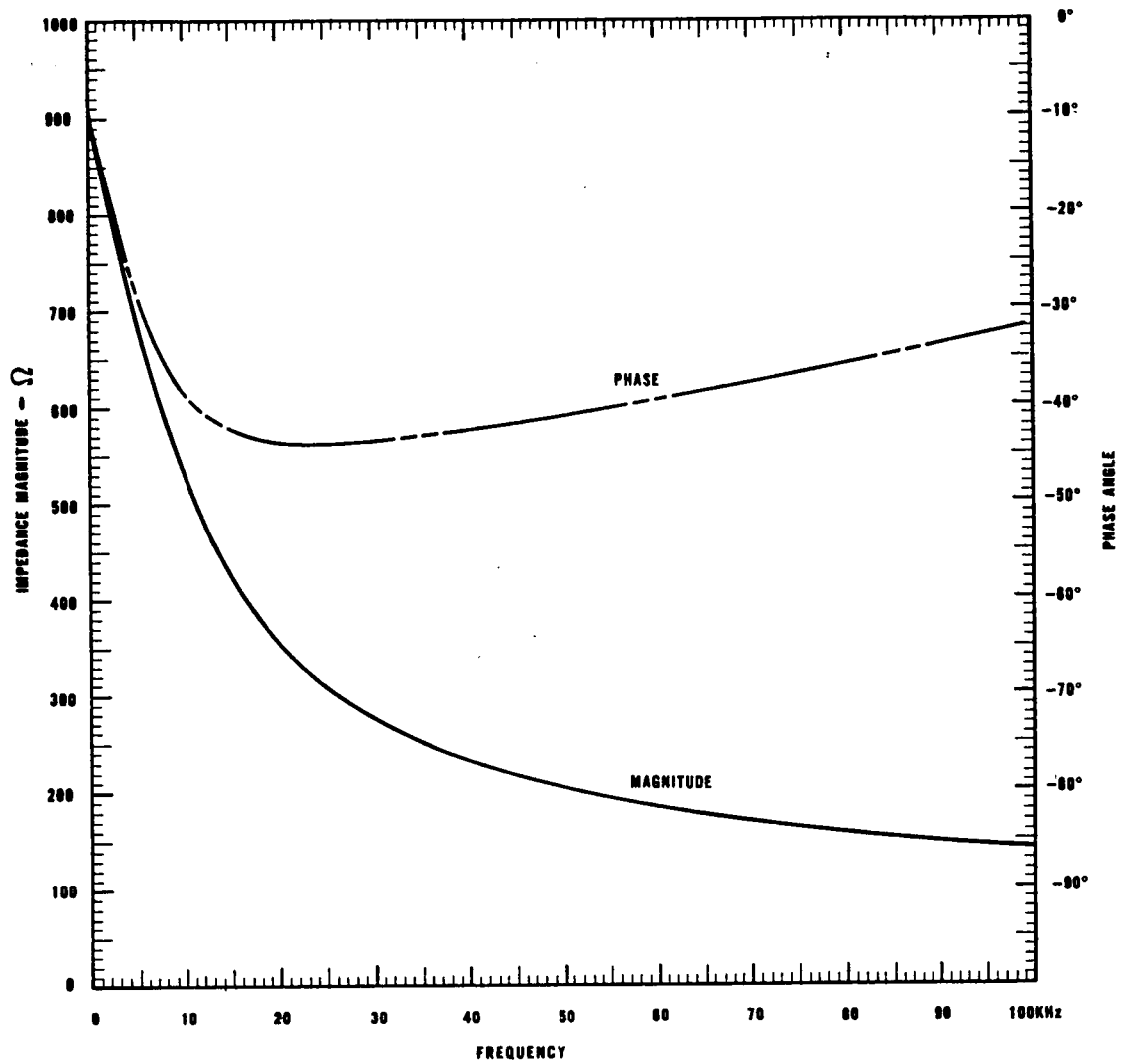


Figure 5-10. Line impedance of a 252 ft braided sheath type K thermocouple cable with a load of 750 ohms grounded at receiving end.

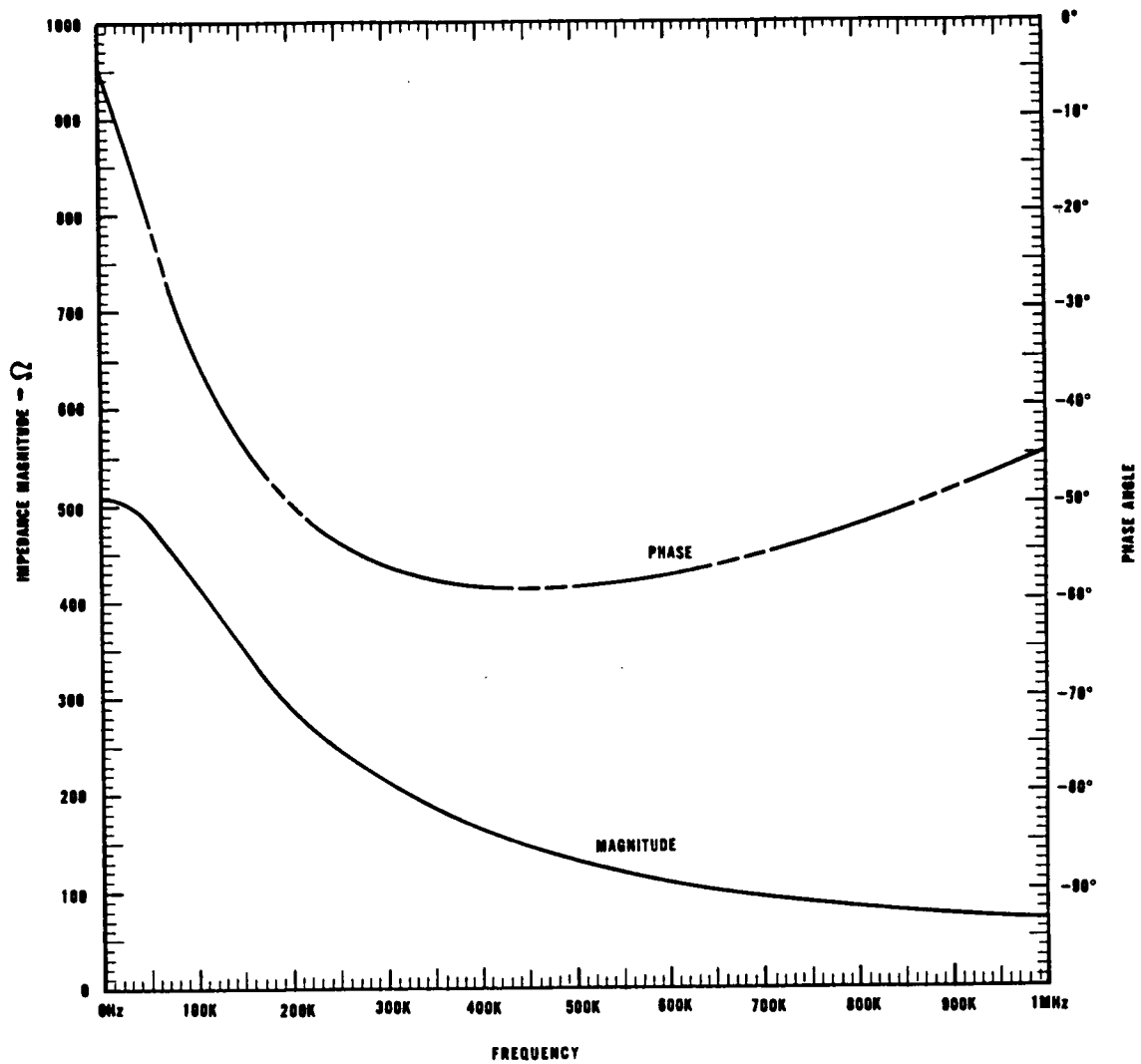


Figure 5-11. Line impedance of a 31 ft solid sheath type K thermocouple cable with a load of 470 ohms and the sheath ungrounded.

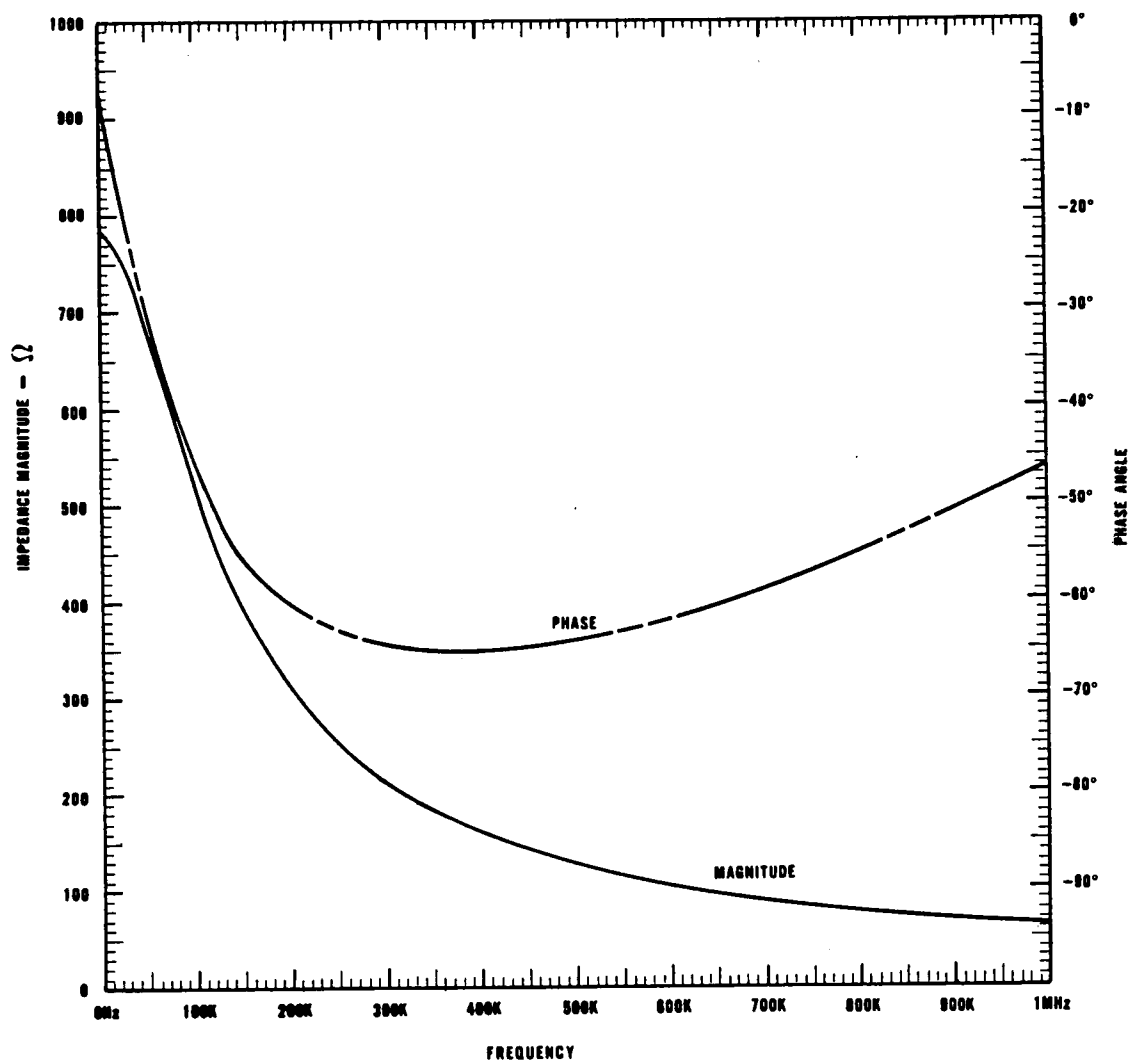


Figure 5-12. Line impedance of a 31 ft solid sheath type K thermocouple cable with a load of 750 ohms and the sheath ungrounded.

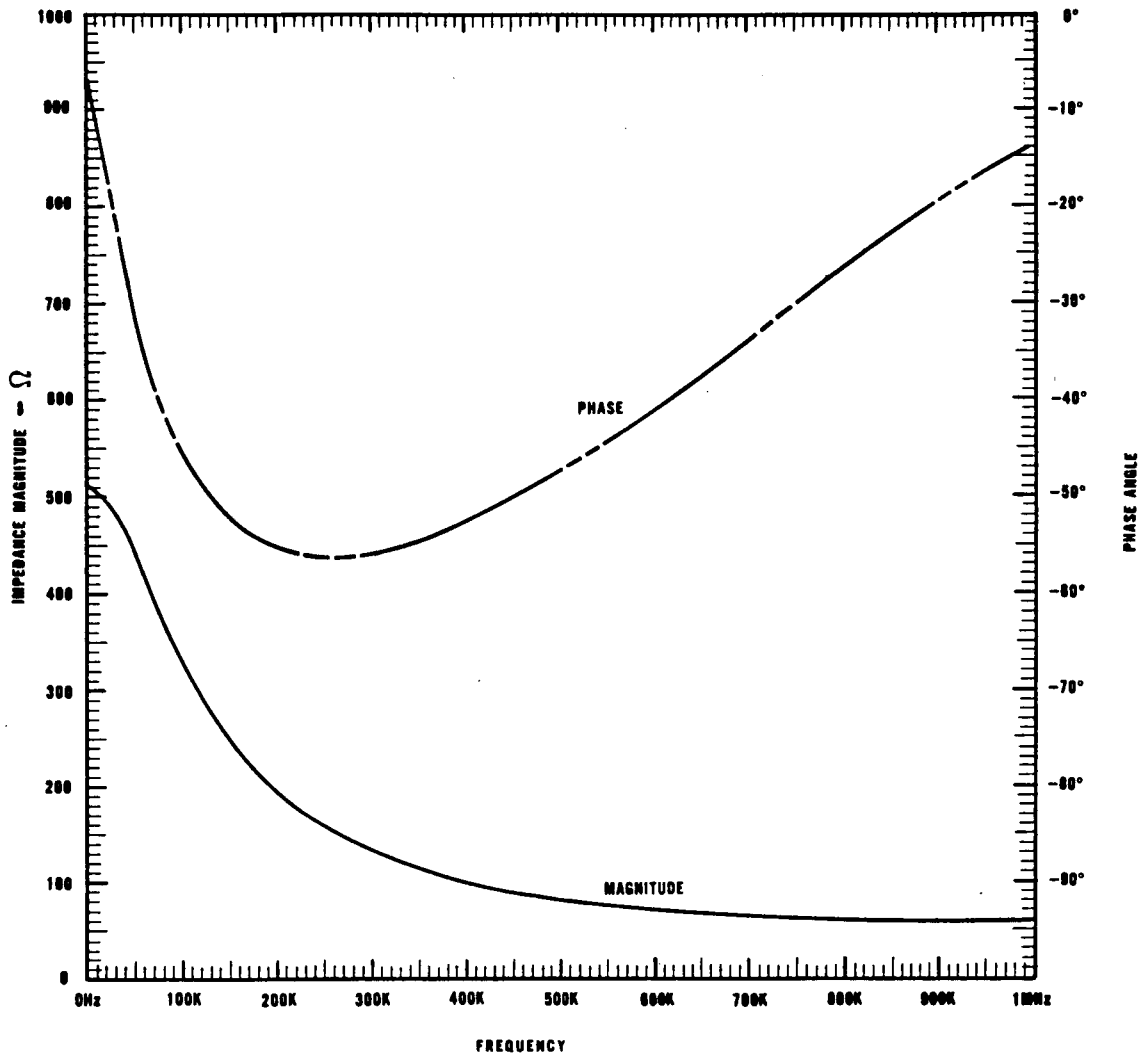


Figure 5-13. Line impedance of a 31 ft solid sheath type K thermocouple cable with a load of 470 ohms grounded at receiving end.

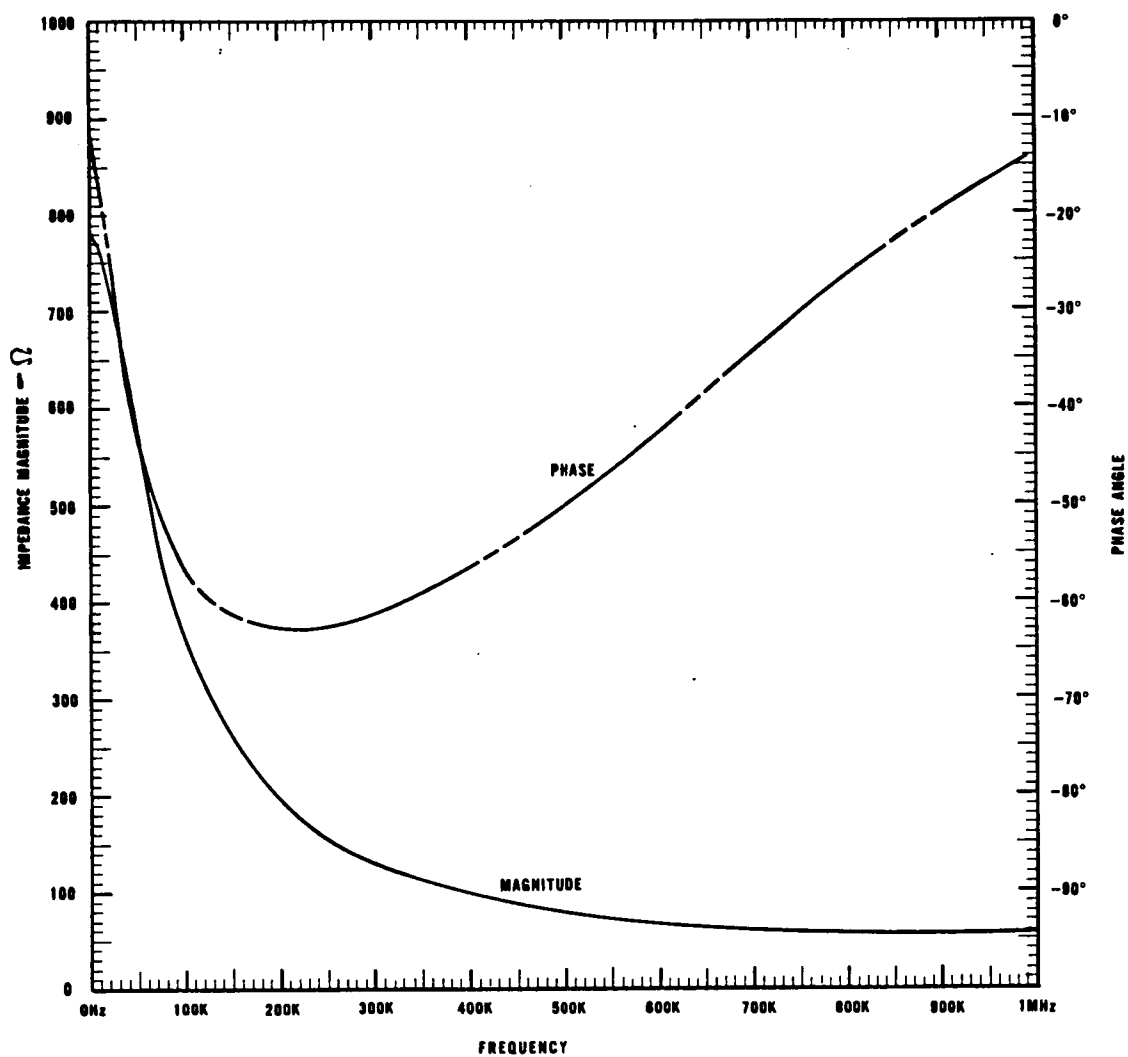


Figure 5-14. Line impedance of a 31 ft solid sheath type K thermocouple cable with a load of 750 ohms grounded at receiving end.

Table 5-1. Impedance Parameters for Computer Model

		Ribbon Sheath (length, 252 ft)	Solid Sheath (length 31 ft)
Resistance	Lead 1	0.23 Ω /ft	0.32 Ω /ft
	Lead 2	0.57 Ω /ft	0.84 Ω /ft
	Sheath	0.32 Ω /ft	0.10 Ω /ft
Inductance	Lead 1	0.5 μ H/ft	0.5 μ H/ft
	Lead 2	0.5 μ H/ft	0.5 μ H/ft
	Sheath	0.03 μ H/ft	0.03 μ H/ft
Resistance	Lead 1 - Lead 2	1.27 $M\Omega$ /ft	275 $G\Omega$ /ft
	Lead 1 - Sheath	1.70 $M\Omega$ /ft	236 $G\Omega$ /ft
	Lead 2 - Sheath	1.78 $M\Omega$ /ft	208 $G\Omega$ /ft
Capacitance	Lead 1 - Lead 2	30 pF/ft	20 pF/ft
	Lead 1 - Sheath	60 pF/ft	80 pF/ft
	Lead 2 - Sheath	60 pF/ft	80 pF/ft

an identifier, information is needed about the crossover frequency. The crossover frequency is the point where a change in the impedance at the end of the line does not affect the magnitude of the voltage across the line. A computer simulation of the identifier and line was made on the two cables developed above for a frequency range of 5 KHz to 1 MHz. The identifier was connected to each of these cables and the identifier's modulation voltage was measured for a frequency range of 5 KHz to 1 MHz and the crossover frequency of the measured, calculated, and computed modulation voltages can be compared in Table 5-2 and 5-3. Table 5-3 has additionally a column where the length of the ribbon cable was changed to that of the solid cable to compare the crossover frequencies of two similar cables with the same length.

Table 5-2. Ribb on Stainless Steel Sheath Type K
Thermocouple Cable with a Lead Size
of 33 mil

Frequency	Measured ^a	Computed from impedance ^b	Computed from model ^c
Grounded			
5K	0.020	0.033	0.030
10K	0.040	0.025	0.027
20K	0.026	0.016	0.018
30K	0.016	0.005	0.010
40K	0.00	-0.001	0.003
50K	-0.004	-0.005	-0.001
60K	-0.005	-0.003	-0.003
Ungrounded			
5K	0.046	0.033	0.030
10K	0.069	0.031	0.029
20K	0.066	0.027	0.022
30K	0.035	0.020	0.016
40K	0.013	0.009	0.008
50K	0.007	0.002	0.002
60K	0.00	-0.001	-0.002
70K	-0.008	-0.007	-0.004
80K	-0.018	-0.011	-0.006
90K	-0.025	-0.008	-0.007

^aVoltage difference measured between the high and low impedance state of a sensor identifier normalized to a 1 V carrier.

^bVoltage difference between the high and low impedance state of a simulated identifier computed from a line impedance measurement.

^cVoltage difference between the high and low impedance state of a simulated identifier computed from a model of the two wire line.

Table 5-3. Solid Stainless Steel Sheath Type K Thermocouple Cable with a Lead Size of 22 mil

Frequency	Measured ^a	Computed from impedance ^b	Computed from model ^c	Computed from similar model ^d
Grounded				
50K	0.079	0.048	0.048	
100K	0.070	0.039	0.041	
200K	0.066	0.024	0.023	
300K	0.013	0.008	0.008	
400K	0.002	0.001	0.00	
500K	0.00	-0.006	-0.004	
600K	0.008	-0.017	0.006	
700K	-0.015	-0.016	-0.005	
800K	-0.007	0.00	-0.003	
900K	0.00	0.00	0.00	
1M	0.00	0.00	0.00	
Ungrounded				
50K	0.079	0.051	0.050	0.052
100K	0.079	0.044	0.098	0.048
200K	0.076	0.038	0.037	0.038
300K	0.063	0.026	0.025	0.026
400K	0.046	0.023	0.015	0.016
500K	0.027	0.011	0.007	0.008
600K	0.002	0.001	0.00	0.001
700K	0.003	-0.007	-0.003	-0.002
800K	-0.009	-0.012	0.005	-0.004
900K	-0.023	-0.009	-0.006	-0.006
1M	-0.017	-0.006	-0.007	-0.007

^aVoltage difference measured between the high and low impedance state of a sensor identifier normalized to a 1 V carrier.

^bVoltage difference between the high and low impedance state of a simulated identifier computed from a line impedance measurement.

^cVoltage difference between the high and low impedance state of a simulated identifier computed from a model of the two wire line.

^dVoltage difference between the high and low impedance state of a simulated identifier computed from a model of a similar thermocouple line.

CHAPTER 6

SUMMARIZING DISCUSSION AND AREAS OF FURTHER STUDY

In this thesis, a prototype wire identifier was developed and shown to operate as expected when incorporated into a thermocouple instrument system. A general model for a three wire line was developed to help predict the effect different connecting cables would have on an identifier system. An approximation of the identifier's impedance was made and verified to aid in the computer modeling. The prototype unit operates as expected but many problems still must be overcome before the identifier is marketable.

Inserting a unique digital code in each sensor identifier and keeping track of which code is in which identifier is a formidable task. Several ideas have emerged on how to accomplish this but none have been presently implemented. The hybrid chip identifier could contain read only memory (ROM) that could be encoded at the factory when it is manufactured, however, there would be no way of locally inserting a desired code in the identifier. This would make replacement of faulty identifiers in the field very difficult. Small metallic links could be located inside the sensor connector to determine an identifier code. A special tool used by a local technician could program each identifier before installation by breaking certain links but no backup quality assurance check would be possible for this operation.

Once an identifier has been programmed, it has to be installed in a sensor and then the sensor assembly installed in a system. The problem of knowing which identifier is with which sensor and where the sensor is placed in the system has not been addressed.

If the identifiers are in power plants or production facilities, they may be required to operate normally at high temperatures or may be subjected to vibration. If they are connected to motors, the noise on the AC power line may completely degrade the response of the identifier. Very little environmental testing has been done on the identifier system at this time.

The sensor instrumentation connected to the wire pair being identified may not be protected against large AC excursions on the wire pair for long periods of time and must be protected against the carrier frequency generated by the sensor identifier system.

Selecting a wire pair to be identified and applying a signal to the wire presents a serious multiplexing problem. Every sensor wire in a system must be tied through a single multiplexer to the system computer so this selection may be made. The multiplexer must be low enough impedance that sufficient energy is delivered across the multiplexer and wire pair to power the sensor identifier.

In conclusion, although there is much work to be done before a commercial identifier is available, none of the problems to be overcome are prohibitive to further development. Since the wire identifier would establish more confidence in the reliability of a

large electrical system, development of a commercial identifier should continue as quickly as possible.

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APPENDIXES

APPENDIX A

DERIVATION OF THE TRANSMISSION LINE EQUATIONS FOR A THREE WIRE LINE

From the six terminal, two port network of Figure 4-1, we can easily write five equations,

$$V_H(x + \Delta x) - V_H(x) = -I_H(x)Z_H \Delta x + I_S(x) Z_S \Delta x , \quad (A-1)$$

$$V_L(x + \Delta x) - V_L(x) = -I_L(x)Z_L \Delta x + I_S(x)Z_S \Delta x , \quad (A-2)$$

$$I_H(x + \Delta x) - I_H(x) = -V_H(x + \Delta x) Y_{HS} \Delta x - [V_H(x + \Delta x) \quad (A-3)$$

$$- V_L(x + \Delta x)] Y_{HL} \Delta x ,$$

$$I_L(x + \Delta x) - I_L(x) = -V_L(x + \Delta x) Y_{LS} \Delta x - [V_L(x + \Delta x) \quad (A-4)$$

$$- V_H(x + \Delta x)] Y_{HL} \Delta x , \text{ and}$$

$$I_S(x + \Delta x) - I_S(x) = V_H(x + \Delta x) Y_{HS} \Delta x + V_L \quad (A-5)$$

$$(x + \Delta x) Y_{LS} \Delta x .$$

By letting $\Delta x \rightarrow 0$,

$$\frac{dV_H}{dx} = -I_H Z_H + I_S Z_S , \quad (A-6)$$

$$\frac{dV_L}{dx} = -I_L Z_L + I_S Z_S, \quad (\text{A-7})$$

$$\frac{dI_H}{dx} = -V_H [Y_{HS} + Y_{HL}] + V_L Y_{HL}, \quad (\text{A-8})$$

$$\frac{dI_L}{dx} = -V_L [Y_{LS} + Y_{HL}] + V_H Y_{HL}, \text{ and} \quad (\text{A-9})$$

$$\frac{dI_S}{dx} = V_H Y_{HS} + V_L Y_{LS}. \quad (\text{A-10})$$

By taking the second derivative of (A-7) and (A-8),

$$\frac{d^2 V_H}{dx^2} = -\frac{dI_H}{dx} Z_H + \frac{dI_S}{dx} Z_S, \text{ and} \quad (\text{A-11})$$

$$\frac{d^2 V_L}{dx^2} = -\frac{dI_L}{dx} Z_L + \frac{dI_S}{dx} Z_S. \quad (\text{A-12})$$

Let ' denote $\frac{d}{dx}$ and '' denote $\frac{d^2}{dx^2}$.

By substituting (A-8), (A-9), and (A-10) into (A-11) and (A-12),

$$V_L'' + Z_H [-V_H (Y_{HS} + Y_{HL}) + V_L Y_{HL}] - Z_S [V_H Y_{HS} + V_L Y_{LS}] = 0, (\text{A-13})$$

and

$$V_L'' + Z_L [-V_L (Y_{LS} + Y_{HL}) + V_H Y_{HL}] - Z_S [V_H Y_{HS} + V_L Y_{LS}] = 0. (\text{A-14})$$

or

$$V_H'' + K_{H1} V_H + K_{L2} V_L = 0, \text{ and} \quad (\text{A-15})$$

$$V_L'' + K_{L1} V_L + K_{H2} V_H = 0. \quad (\text{A-16})$$

where

$$K_{H1} = -Z_H (Y_{HS} + Y_{HL}) - Z_S Y_{HS}, \quad (\text{A-17})$$

$$K_{L2} = Z_H Y_{HL} - Z_S Y_{LS}, \quad (\text{A-18})$$

$$K_{L1} = -Z_L (Y_{LS} + Y_{HL}) - Z_S Y_{LS}, \quad (\text{A-19})$$

$$K_{H2} = Z_L Y_{HL} - Z_S Y_{HS}. \quad (\text{A-20})$$

To further simplify write

$$V_L = - \frac{V_H'' + K_{H1} V_H}{K_{L2}}. \quad (\text{A-21})$$

Let D denote $\frac{d}{dx}$,

$$V_L = - \frac{(D^2 + K_{H1}) V_H}{K_{L2}}. \quad (\text{A-22})$$

Substituting into (11)

$$(D^2 + K_{L1}) \left[- \frac{(D^2 + K_{H1}) V_H}{K_{L2}} \right] + K_{H2} V_H = 0 . \quad (A-23)$$

or

$$[D^4 + D^2 (K_{L1} + K_{H1}) + K_{L1} K_{H1}] V_H - K_{H2} K_{L2} V_H = 0 . \quad (A-24)$$

The characteristic equation is:

$$D^4 + C_1 D^2 + C_2 = 0 , \quad (A-25)$$

where

$$C_1 = K_{L1} + K_{H1} , \text{ and} \quad (A-26)$$

$$C_2 = K_{L1} K_{H1} - K_{H2} K_{L2} . \quad (A-27)$$

Therefore,

$$V_H = \sum_{n=1}^4 A_n e^{\alpha_n x} , \quad (A-28)$$

where

$$\alpha = \pm \sqrt{-\frac{C_1}{2} \pm \sqrt{\frac{C_1^2}{4} - C_2}} \quad (A-29)$$

From (A-21),

$$V_L = - \sum_{n=1}^4 \frac{\alpha_n^2 A_n e^{\alpha_n x} + K_{H1} \sum_{n=1}^4 A_n e^{\alpha_n x}}{K_{L2}}, \quad (A-30)$$

$$V_L = - \frac{1}{K_{L2}} \sum_{n=1}^4 (\alpha_n^2 + K_{H1}) A_n e^{\alpha_n x}, \text{ and} \quad (A-31)$$

$$V_L = \sum_{n=1}^4 B_n e^{\alpha_n x}, \quad (A-32)$$

where

$$B_n = - \frac{\alpha_n^2 + K_{H1}}{K_{L2}} A_n. \quad (A-33)$$

From (A-10),

$$I_S' = Y_{HS} \sum_{n=1}^4 A_n e^{\alpha_n x} + Y_{LS} \sum_{n=1}^4 B_n e^{\alpha_n x}, \quad (A-34)$$

$$= \sum_{n=1}^4 (A_n Y_{HS} + B_n Y_{LS}) e^{\alpha_n x}, \quad (A-35)$$

$$I_S = \left[\sum_{n=1}^4 (A_n Y_{HS} + B_n Y_{LS}) \int e^{\alpha_n x} \right] + C_I, \quad (A-36)$$

$$= \left[\sum_{n=1}^4 \frac{A_n Y_{HS} + B_n Y_{LS}}{\alpha_n} e^{\alpha_n x} \right] + C_I, \quad (A-37)$$

$$= \sum_{n=1}^4 C_n e^{\alpha_n x} + C_I, \quad (A-38)$$

where

$$C_n = \frac{A_n Y_{HS} + B_n Y_{LS}}{\alpha_n}. \quad (A-39)$$

From (A-6),

$$I_H = - \frac{V_H' - I_S Z_S}{Z_H}, \quad (A-40)$$

$$I_H = - \frac{1}{Z_H} \left[\sum_{n=1}^4 A_n \alpha_n e^{\alpha_n x} - Z_S \left(\sum_{n=1}^4 C_n e^{\alpha_n x} + C_I \right) \right], \text{ and} \quad (A-41)$$

$$I_H = \frac{Z_S C_I}{Z_H} + \sum_{n=1}^4 D_n e^{\alpha_n x}, \quad (A-42)$$

where

$$D_n = \frac{-A_n \alpha_n + Z_S C_n}{Z_H} . \quad (A-43)$$

From (A-7),

$$I_L = - \frac{V_L' - I_S Z_S}{Z_L} , \quad (A-44)$$

$$= - \frac{1}{Z_L} \left[\sum_{n=1}^4 B_n \alpha_n e^{\alpha_n x} - Z_S \left(\sum_{n=1}^4 C_n e^{\alpha_n x} + C_I \right) \right] , \text{ and} \quad (A-45)$$

$$= \frac{Z_S C_I}{Z_L} + \sum_{n=1}^4 E_n e^{\alpha_n x} , \quad (A-46)$$

where

$$E_n = \frac{-B_n \alpha_n + Z_S C_n}{Z_L} . \quad (A-47)$$

Defining all undetermined constants in terms of A_n 's;

$$B_n = Q_{Bn} A_n , \quad (A-48)$$

$$Q_{B_n} = - \frac{\alpha_n^2 + K_{H1}}{K_{L2}}, \quad (A-49)$$

$$C_n = Q_{C_n} A_n, \quad (A-50)$$

$$Q_{C_n} = \frac{1}{\alpha_n} \left[Y_{HS} + Y_{LS} \left(- \frac{\alpha_n^2 + K_{H1}}{K_{L2}} \right) \right], \quad (A-51)$$

$$D_n = Q_{Dn} A_n, \quad (A-52)$$

$$Q_{D_n} = \frac{1}{Z_H} \left[-\alpha_n + Z_S \left\{ \frac{1}{\alpha_n} \left[Y_{HS} + Y_{LS} \left(\frac{-\alpha_n^2 + K_{H1}}{K_{L2}} \right) \right] \right\} \right], \quad (A-53)$$

$$E_n = Q_{E_n} A_n, \text{ and} \quad (A-54)$$

$$Q_{E_n} = \frac{1}{Z_L} \left[-\alpha_n \left(\frac{-\alpha_n^2 + K_{H1}}{K_{L2}} \right) + Z_S \left\{ \frac{1}{\alpha_n} \left[Y_{HS} + Y_{LS} \left(\frac{-\alpha_n^2 + K_{H1}}{K_{L2}} \right) \right] \right\} \right]. \quad (A-55)$$

Then

$$V_H(x) = \sum_{n=1}^4 A_n e^{\alpha_n x}, \quad (A-56)$$

$$V_L(x) = \sum_{n=1}^4 Q_{Bn} A_n e^{\alpha_n x}, \quad (A-57)$$

$$I_S(x) = C_I + \sum_{n=1}^4 Q_{Cn} A_n e^{\alpha_n x}, \quad (A-58)$$

$$I_H(x) = \frac{Z_{S^C I}}{Z_H} + \sum_{n=1}^4 Q_{Dn} A_n e^{\alpha_n x}, \text{ and} \quad (A-59)$$

$$I_L(x) = \frac{Z_{S^C I}}{Z_L} + \sum_{n=1}^4 Q_{En} A_n e^{\alpha_n x}. \quad (A-60)$$

APPENDIX B

PROGRAM TO GIVE FREQUENCY ANALYSIS OF A CABLE
USED FOR SENSOR IDENTIFICATION

```

11  FORMAT (/ 'FREQ=' ,F9.0, ' VO=' , F8.5, ' VS=' ,F8.5, ' VEND =' ,F8.2)
C
C  This program calculates the input impedance between two wires
C  (called high and low) of a 3 wire transmission line. The user
C  specifies the line parameters and the terminating resistance
C  and has a choice of three ways of connecting the shield. The
C  user may also get diagnostic printouts of some of the inter-
C  mediate variable values if he desires.
C  The following complex variables are used in the calculations:
C
C  ZH    - The series impedance per length of the "high" wire
C  ZL    - The series impedance per length of the "low" wire
C  ZSH   - The series impedance per length of the shield
C  YHL   - The shunt admittance per length between high and low
C  YHSH  - The shunt admittance per length between low and shield
C  YLSH  - The shunt admittance per length between high and
C          shield
C  VHO   - The phasor voltage from high to shield at the sensor
C          end
C  VLO   - The phasor voltage from low to shield at the sensor
C          end
C  IHO   - The phasor current in the high wire at the sensor end

```

C ILO - The phasor current in the low wire at the sensor end
 C ISHO - The phasor current in the shield at the sensor end
 C VHL - The phasor voltage from high to shield at the receiving
 C end
 C VLL - The phasor voltage from low to shield at the receiving
 C end
 C IHL - The phasor current in the high wire at the receiving
 C end
 C ILL - The phasor current in the low wire at the receiving
 C end
 C ISHL - The phasor current in the shield at the receiving end
 C VLINE - A dummy variable to hold the voltage developed across
 C the line

 Complex*16 KH1, KH2, KL1, KL2, ZH, ZL, ZSH, YHL, YHSH, YLSH,
 VHO, VLO, IHO1, ILO, ISHO, VHL, VLL, IHL, ILL, ISHL, COEF1,
 COEF2, ALPHA(4), A(4)2, QB(4), QC(4), QD(4), QE(4), MAT(5,5),
 FORVEC(5), SOLVEC(5), CI3, ZIN, BIG, RATIO, VLINE

 C
 C IFLAG - A flag to determine the limit desired 1, 2, or 3
 integer BIGSUB, IFLAG.

 C
 C The following real quantities are also used in calculating the
 C input impedance:
 C

C	LH	- The inductance per length of the high wire
C	LL	- The inductance per length of the low wire
C	LSH	- The inductance per length of the shield
C	RH	- The resistance per length of the high wire
C	RL	- The resistance per length of the low wire
C	RSH	- The resistance per length of the shield
C	CHL	- The capacitance per length between high and low
C	CHSH	- The capacitance per length between high and shield
C	CLSH	- The capacitance per length between low and shield
C	RHL	- The resistance per length between high and low
C	RHSH	- The resistance per length between high and shield
C	RLSH	- The resistance per length between low and shield
C	LENGTH	- The length of the line
C	FREQ	- The frequency at which an input impedance calculation
C		is made
C	LFREQ	- The lower frequency limit
C	HFREQ	- The high frequency limit
C	SFREQ	- The frequency step size
C	VMIN	- The minimum voltage allowed for the sensor
C		identifier
C	RS	- The resistance of the sensor (the terminating
C		resistor)
C	W	- The radian frequency at which an input impedance
C		calculation is made
C	RSLOW	- The end line short circuit resistance

C RSHIGH - The end line open circuit resistance
 C RI - The source resistance
 C LIM(1) - The maximum frequency before the crossover point that
 C allows vmin difference between the short and open
 C circuit load resistances on the line at the source
 C resistor
 C LIM(2) - The minimum frequency after the crossover point that
 C allows vmin difference between the short and open
 C circuit load resistances on the line at the source
 C resistor
 C LIM(3) - The maximum frequency after the crossover point that
 C allows vmin difference between the short and open
 C circuit load resistances on the line at the source
 C resistor
 C VSHORT - An intermediate short circuit line voltage
 C VOPEN - An intermediate open circuit line voltage
 C VIN - The input voltage magnitude
 C VEND - The end line voltage
 C VLIMIT - The minimum allowable peak to peak sensor voltage
 C X - Dummy variable used for skin effect
 Real*8 LH, LL, LSH, LENGTH, RH, RL, RSH, CHL, CHSH, CLSH, FREQ,
 LFREQ1, SFREQ, RS, W, HFREQ, VMIN, RSLow, RSHIGH, RI, LIM(4),
 VIN, VEND, VLIMIT2, RHL, RSH, RLSH, X
 C

C "TYPFLG" is an alphabetic flag which the user enters to choose
C which type of shield connection he wants to assume.

BYTE TYPELG

C
C "Pi" is the ratio of the circumference to the diameter of a
C circle.

Pi = 3.14159265

OPEN (unit=2,NAME='D.TXT',TYPE='UNKNOWN', ACCESS='SEQUENTIAL',
FORM='FORMATTED')

C
C Ask user how the shield is to be connected.

C
Ask-for-type-of-line

C
C Get from the user the resistance, inductance, and capacitance
C per unit length and the terminating resistance values.

C
Get-line-parameters

C In this loop the identifier usability is calculated for
C successive values of frequency between LFREQ and HFREQ where
C the resolution is SFREQ.

C

```
IFLAG = 1
```

```
FREQ = LFREQ
```

```
Until (FREQ.GT.HFREQ)
```

```
C
```

```
C   This section solves for the arbitrary constants in the
C   solutions for voltage and current which are determined by the
C   boundary conditions.
```

```
C
```

```
RS = RLOW
```

```
Solve-for-constants
```

```
C
```

```
C   Once the constants are known, the voltages and currents and
C   then the input impedance can be calculated.
```

```
C
```

```
Calculate-input-impedance
```

```
VSHORT = CDABS (VLINE)
```

```
C
```

```
C   Repeat for open circuit conditions
```

```
C
```

```
RS = RSHIGH
```

```
Solve-for-constants
```

```
Calculate-input-impedance
```

```
VOPEN = CDABS (VLINE)
```

```
TYPE 11, FREQ, VOPEN,VSHORT,VEND
```

```
WRITE(2,11)FREQ, VOPEN,VSHORT,VEND
```

C

C

C

Calculate-voltage-minimum-frequency-range

FREQ = FREQ + SFREQ

FIN

C

C Show the user his results.

C

Display-results

CLOSE (Unit = 2, DISPOSE = 'PRINT/DELETE')

STOP

C

C Get a value of "TYPFLG" of "F", "R", or "B" to determine

C whether the shield is floating, grounded at the receiving end

C only, or grounded at both ends.

C

To ask-for-type-of-line

TYPE 10

10 FORMAT (' How is shield connected?:' /

1' Floating? (F)' /

2' Grounded at receiving end only? (R)')

READ (5,20), TYPFLG

20 FORMAT (A1)

FIN

C

C Get the "per length" parameters of the line, the terminating

C resistance, and the frequency range and resolution.

C

To get-line-parameters

TYPE 30

30 FORMAT (///' Enter the following: (with decimal points)'/

1' Series resistivity (in ohms/length) of:'/

2' A. High side'/

3' B. Low side'//)

4' C. Shield'//)

READ (5,40), RH, RL, RSH

40 FORMAT (F14.6)

TYPE 31

31 FORMAT (///' Series inductance (in microhenrys/length) of:'/

1' A. High side'/

2' B. Low side'/

3' C. Shield'//

READ (5,40)LH,LL,LSH

TYPE 34

34 FORMAT (///' SHUNT RESISTANCE (IN OHMS/LENGTH) OF: '/

1' A. High to low'/

2' B. High to shield'/

3' C. Low to shield'/

READ (5,40),RHL,RHSH,RLSH

TYPE 32

32 FORMAT (///' Shunt capacitance (in picofarads/length) of: '/

1' A. High to low' /

2' B. High to shield' /

3' C. Low to shield' /)

READ (5,40)CHL,CHSH,CLSH

TYPE 33

33 FORMAT (///' 1. Sensor shorted mode resistance in ohms' /

1' 2. Sensor open mode resistance in ohms' /

2' 3. Minimum allowable voltage difference short to open' /

3' 4. Length of line' /

4' 5. Start frequency in KHz' /

5' 6. End frequency in KHz' /

6' 7. Frequency step size in KHz' /

7' 8. Source resistance' /

8' 9. Input voltage peak to peak' /)

9' 10. Minimum sensor voltage' /)

READ (5,40)RSLOW,RSHIGH,VMIN,LENGTH,LFREQ,HFREQ,SFREQ,RI,VIN

1,VLIMIT

C

C Convert to standard units (Henrys, Farads, Hz) $LL = LH/1.E6$

C

$LH = LH/1.E6$

$LL = LL/1.E6$

$LSH = LSH/1.E6$

CHL = CHL/1.E12

CHSH = CHSH/1.E12

CLSH = CLSH/1.E12

HFREQ = HFREQ*1.E3

LFREQ = LFREQ*1.E3

SFREQ = SFREQ*1.E3

RHL=1./RHL

RHSH=1./RHSH

RLSH=1./RLSH

FIN

C

C Solve for the arbitrary constants in the solutions for voltage
C and current on the line.

C

C This solution process follows a write-up by M. J. Roberts.

C Refer to it for exact meaning of variables.

C

To solve-for-constants

Modify rseistances

W=FREQ*2.*PI

ZH=DCMPLX(RH,W*LH)

ZL=DCMPLX(RL,W*LL)

ZSH=DCMPLX(RSH,W*LSH)

YHL=DCMPLX(RHL,W*CHL)

YHSH=DCMPLX(RHSH,W*CHSH)

```

YLSH=DCMPLX(RLSH,W*CLSH)
KH1=-ZH*(YHSH+YHL)-ZSH*YHSH
KL2=ZH*YHL-ZSH*YLSH
KL1=-ZL*(YLSH+YHL)-ZSH*YLSH
KH2=ZL*YHL-ZSH*YHSH
COEF1=KL1+KH1
COEF2=KL1*KH1-KH2*KL2
ALPHA(1)=CDSQRT(-(COEF1/2.)+CDSQRT((COEF1**2/4.)-COEF2))
ALPHA(2)=CDSQRT(-(COEF1/2.)-CDSQRT((COEF1**2/4.)-COEF2))
ALPHA(3)=-ALPHA(1)
ALPHA(4)=-ALPHA(2)
DO (I=1,4)
  QB(I)=-ALPHA(I)**2+KH1)/KL2
  QC(I)=(YHSH+YLSH*(-(ALPHA(I)**2+KH1)/KL2))/ALPHA(I)
  QD(I)=(-ALPHA(I)+ZSH*(YHSH+YLSH*(-(ALPHA(I)**2+KH1)/KL2))
  1/ALPHA(I))/ZH
  QE(I)=(-ALPHA(I)*(-(ALPHA(I)**2+KH1)/KL2)+ZSH*(YHSH+YLSH*
  1(-(ALPHA(I)**2+KH1)/KL2))/ALPHA(I))/ZL
FIN
DO (I=1,4)
  MAT(1,I)=QD(I)+QE(I)
  MAT(2,I)=QC(I)
  MAT(3,I)=1.-QB(I)-RS*QE(I)

```

C

C If the shield is floating, use the following values.

C

When (TYPFLG.EQ.'F')

$$\text{MAT}(4, I) = \text{CDEXP}(\text{ALPHA}(I) * \text{LENGTH}) * (1. - \text{QB}(I) - \text{RI} * \text{QD}(I))$$

$$\text{MAT}(5, I) = \text{CDEXP}(\text{ALPHA}(I) * \text{LENGTH}) * (\text{QD}(I) + \text{QE}(I))$$

FIN

C

C If the shield is not floating (it is grounded at the receiving
C end only), use these values.

C

Else

$$\text{MAT}(4, I) = \text{CDEXP}(\text{ALPHA}(I) * \text{LENGTH}) * (1 - \text{RI} * \text{QD}(I))$$

$$\text{MAT}(5, I) = \text{CDEXP}(\text{ALPHA}(I) * \text{LENGTH}) * \text{QB}(I)$$

FIN

FIN

C

C If it is not true that both ends of the shield are grounded,
C use these values instead.

C

$$\text{MAT}(1, 5) = (\text{ZSH}/\text{ZH}) + (\text{ZSH}/\text{ZL})$$

$$\text{MAT}(2, 5) = 1.$$

$$\text{MAT}(3, 5) = -\text{RS} * \text{ZSH}/\text{ZL}$$

C

C If the shield is floating, use the following values.

C

```
WHEN (TYPFLG.EQ.'F')
```

```
MAT(4,5)=ZS*RI/ZH
```

```
MAT(5,5)=MAT(1,5)
```

```
FIN
```

```
C
```

```
C   If the shield is not floating (it is grounded at the receiving
C   end only), use these values.
```

```
C
```

```
ELSE
```

```
MAT(4,5)=-ZS*RI/ZH
```

```
MAT(5,5)=0.
```

```
FIN
```

```
DO(I=1,5)
```

```
FORVEC(I)=0.
```

```
FIN
```

```
C
```

```
C   If it is not true that both ends of the shield are grounded,
C   use these values instead.
```

```
C
```

```
FORVEC(4)=1
```

```
FIN
```

```
To modify-resistances
```

```
X=.1585*SQRT((FREQ*30.48)/(RH*1.E6))
```

```
Calculate-skin-effect
```

```
RH=RH*X
```

$X = .1585 * \text{SQRT}((\text{FREQ} * 30.48) / (\text{RL} * 1.E6))$

Calculate-skin-effect

$\text{RL} = \text{RL} * X$

$X = .1585 * \text{SQRT}((\text{FREQ} * 30.48) / (\text{RSH} * 1.E6))$

Calculate-skin-effect

$\text{RSH} = \text{RSH} * X$

FIN

To calculate-skin-effect

When (X.GT.2.)

FIN

ELSE

$X - 1.$

FIN

FIN

C

C Here the input impedance is calculated from the voltages and
C currents at the receiving end.

C

To calculate-input-impedance

C

C Solve for the arbitrary constants

C

Solve-system-of-equations

IF (DIAGFL.EQ.'D')

TYPE 1060, (SOLVEC(I), I=1, 5)

1060 FORMAT(// 'SOLVEC(1)=',2(1PE15.7)/

1 ' SOLVEC(2) = ',2(1PE15.7)/

2 ' SOLVEC(3) = ',2(1PE15.7)/

3 ' SOLVEC(4) = ',2(1PE15.7)/

4 ' SOLVEC(5) = ',2(1PE15.7)/

FIN

A(1)=SOLVEC(1)

A(2)=SOLVEC(2)

A(3)=SOLVEC(3)

A(4)=SOLVEC(4)

CI=SOLVEC(5)

C

C Calculate the voltages and currents at the ends of the line.

C

VHO=0.

VHL=0.

VLO=0.

VLL=0.

IHO= SH*CI/ZH

IHL=ZSH*CI/ZH

ILO=ZSH*CI/ZL

ILL=ZSH*CI/ZL

ISHO=CI

ISHL=CI

DO (I=1,4)

```

VHO=VHO+A(I)
VHL=VHL+A(I)*CDEXP(ALPHA(I)*LENGTH)
VLO=VLO+QB(I)*A(I)
VLL=VLL+QB(I)*A(I)*CDEXP(ALPHA(I)*LENGTH)
IHO=IHO+QD(I)*A(I)
IHL=IHL+QD(I)*A(I)*CDEXP(ALPHA(I)*LENGTH)
ILO=ILO+QE(I)*A(I)
ILL=ILL+QE(I)*A(I)*CDEXP(ALPHA(I)*LENGTH)
ISHO=ISHO+QC(I)*A(I)
ISHL=ISHL+QC(I)*A(I)*CDEXP(ALPHA(I)*LENGTH)
FIN

```

C

C Calculate the line input impedance "ZIN" and then the line
C voltage

C

```

ZIN=1./IHL
VEND=VIN*CDABS(VHO-VLO)
VLINE=VIN*ZIN/(ZIN+RI)
FIN

```

C

C This procedure solves the system of equations for the arbitrary
C constants by the method of upper-triangularization-and-back-
C substitution.

To solve-system-of-equations

DO (I=1,4)

C

C If the biggest (in magnitude) value in the column (below the
C diagonal) is not in the diagonal, add two rows to make it be on
C the diagonal. This helps avoid numerical difficulties when the
C diagonal element is very small.

Find-biggest-value-in-column-I-below-diagonal

IF (BIGSUB.NE.I)

DO (J=1,5)

MAT(I,J)=MAT(I,J)+MAT(BIGSUB,J)

FIN

FORVEC(I)=FORVEC(I)+FORVEC(BIGSUB)

C Type-matrix-and-forcing-vector

FIN

C

C Here, by adding row coefficients (multiplied by correctly
C chosen constants) make the elements below the diagonal zero.

C

IP1=I+1

DO (J=IP1,5)

IF (MAT(J,I).NE.DCMPLX(0.D0,0.D0))

RATIO=MAT(J,I)/MAT(I,I)

DO (L=1,5)

```

MAT(J,L)=MAT(J,L)-(MAT(I,L)*RATIO)

FIN

MAT(J,I)=0.

FORVEC(J)=FORVEC(J)-(FORVEC(I)*RATIO)

FIN

FIN

C   Type-Matrix-and-forcing-vector

FIN

C   Type-matrix-and-forcing-vector

C

C   Once the matrix is upper-triangularized the back substitution
C   begins.

SOLVEC(5)=FORVEC(5)/MAT(5,5)

DO (I=2,5)

  IMODIF=6-I

  IMP1=IMODIF+1

  SOLVEC(IMODIF)=FORVEC(IMODIF)

  DO (J=IMP1,5)

    SOLVEC(IMODIF)=SOLVEC(IMODIF)-(MAT(IMODIF,J)*SOLVEC(J))

  FIN

  SOLVEC(IMODIF)=SOLVEC(IMODIF)/MAT(IMODIF,IMODIF)

FIN

FIN

C

```

C Here the biggest value (in magnitude) in the present column
 C below the diagonal is found.

C

To-find-biggest-value-in-column-I-below-diagonal

BIGSUB=1

BIG=0.

DO (ITEMP=1,5)

IF (CDABS(MAT(ITEMP,I)).GT.CDABS(BIG))

BIGSUB+ITEMP

BIG=MAT(ITEMP,I)

FIN

FIN

FIN

C

C This procedure prints out the range of frequencies available
 C for use by the sensor identifier

C

To display-results

TYPE 1000, LFREQ,LIM(1)

WRITE(2,1000)LFREQ,LIM(1)

1000 FORMAT(///' for a frequency range of ',1F9.2,' Hz to ',

1' ',1F9.2,' Hz'/)

IF (IFLAG.GT.2)

WRITE(2,1001)LIM(2),LIM(3)

TYPE 1001,LIM(2),LIM(3)

```

1001  FORMAT(22X,' AND ',1F9.2,' Hz to ',1F9.2,' Hz')
      FIN
      WRITE(2,1002)VIN,RI,SFREQ
      TYPE 1002,VIN,RI,SFREQ
1002  FORMAT(/' The sensor identifier should operate correctly with'
      1,' An input voltage of ',1F9.2,' volts, a source impedance'
      2,' of ',1F9.0,' ohms, and a frequency resolution of '
      3/,1F9.2, Hertz.'///
      FIN

C
C  This routine calculates the three frequency limit values.
C

      To calculate-voltage-minimum-frequency-range
      WHEN (IFLAG.EQ.1)
      Calculate-high-limit
      FIN
      ELSE
      WHEN (IFLAG.EQ.2)
      WHEN (ABS(VSHORT-VOPEN).LT.VMIN)
      IF (VEND.GE.VLIMIT)
      LIM(IFLAG)=FREQ
      FIN
      ELSE
      IFLAG=3
      FIN

```

FIN

ELSE

Calculate-high-limit

FIN

FIN

FIN

C

C Routine to find frequency above which the line voltage change

C is less than VMIN

C

To calculate-high-limit

WHEN (ABS(VSHORT-VOPEN).GE.VMIN)

IF (VEND.GE.VLIMIT)

LIM(IFLAG)=FREG

FIN

FIN

ELSE

IFLAG=IFLAG+1

FIN

FIN

END

VITA

David McNeilly was born March 6, 1953 in Somerset, Kentucky. He attended elementary schools in that city and was graduated from Somerset High School in 1971. The following September he entered Somerset Community College. In June 1976 he joined the United States Air Force for a four year tour. In June 1977 he enrolled in an B.S.E.E. curriculum in The University of Tennessee, Knoxville, graduating three years later with high honors. He is presently employed at Oak Ridge National Laboratory. He is a member of Eta Kappa Nu, Tau Beta Pi, and the National Honor Society.