Fault location system
by Nicholas Constandinos Petrakis

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering
Montana State University

Abstract:
A major concern of power companies after a power line has been disabled due to a fault is that of restoring power to the customer in the shortest possible time. A lot of time is spent in locating the fault position. The existing methods of fault location may give errors as high as 30% from where the fault occurred.

In this thesis a new system has been investigated which detects faults on power transmission lines and instantly reports their location. The faults addressed here are the ones occurring on transmission poles only.

Each transmission pole or tower is equipped with a unit consisting of a detector, a . microcontroller and a transmitter. The detector's transducers consist of three coils, responsible for detecting line to ground and line to line faults occurring at the pole. In case of a fault, the detection circuitry interrupts the microcontroller which reads a code from a set of switches associated with the pole's location along the transmission line. This code is fed through a modem to the transmitter. The transmitter used is a low power unit having a limited range. Therefore, repeaters are used to relay the fault code to a control room. Upon receiving the code proper action may be taken to alleviate the problem. The repeaters also conduct a self test of the entire communication link every 24 hours to assure its proper functioning.

This Fault Location System has been implemented on a simulated transmission line. Experimental results illustrate the effectiveness of this fault location scheme in determining the faulted pole.

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ABSTRACT

A major concern of power companies after a power line has been disabled due to a fault is that of restoring power to the customer in the shortest possible time. A lot of time is spent in locating the fault position. The existing methods of fault location may give errors as high as 30% from where the fault occurred.

In this thesis a new system has been investigated which detects faults on power transmission lines and instantly reports their location. The faults addressed here are the ones occurring on transmission poles only.

Each transmission pole or tower is equipped with a unit consisting of a detector, a microcontroller and a transmitter. The detector's transducers consist of three coils, responsible for detecting line to ground and line to line faults occurring at the pole. In case of a fault, the detection circuitry interrupts the microcontroller which reads a code from a set of switches associated with the pole's location along the transmission line. This code is fed through a modem to the transmitter. The transmitter used is a low power unit having a limited range. Therefore, repeaters are used to relay the fault code to a control room. Upon receiving the code proper action may be taken to alleviate the problem. The repeaters also conduct a self test of the entire communication link every 24 hours to assure its proper functioning.

This Fault Location System has been implemented on a simulated transmission line. Experimental results illustrate the effectiveness of this fault location scheme in determining the faulted pole.

CHAPTER 1

INTRODUCTION

Background and Problem Definition

Overhead transmission line faults have always been a major concern to power companies because of the financial loss they cause and the disruption in service. Great measures are taken to minimize these faults through better transmission pole design but unfortunately they cannot be entirely eliminated.

There are many causes of faults on transmission lines. For example, material aging and nature's direct interference are some of the factors contributing to insulation breakdown on transmission poles. Insulation breakdown is one of the more frequent faults affecting the transmission line's reliability. Engineers have been attacking this problem since electrical power distribution came into being. Many devices were invented with the sole purpose of finding the exact location of a fault to reduce the outage time.

One method currently used is the Oscillagraph and Fault Study analysis. A fault on the line section of interest is moved along the line (called a sliding fault) until the magnitude of the current obtained from the fault study equals that measured on the oscillagraph[1]. This method produces error around 8.5%. Another fault location device is the Linam Fault Indicator which is mounted on the ground wire of every pole. It can only detect ground faults. It works on the principal of magnetization or an electromechanical switch, to trigger a colored flag in case of a current flowing in the ground wire above a certain threshold. Due to the nature of the fault currents which stretch several poles on either side of the faulted pole, a group of these devices is triggered. The disadvantage of this fault locating scheme is that the segment of transmission line that experiences a fault has to be checked visually to find the triggered devices. After this is accomplished each pole has to be checked to find the damage. This search could take several days and for a long stretch of transmission line this is simply unacceptable.

A third fault location device is one making use of traveling wave timing. This type uses two devices, one on each side of the line, with electronic clocks. Each device records the exact time a traveling wave from a fault reaches its terminal. The incremental difference in traveling wave time is directly related to the fault location. A communication link synchronizes the clocks at each terminal for maximum accuracy, but the communication link's jitter threatens the accuracy of this device[2].

Other kinds of fault location devices study the voltage and current waveform amplitudes during pre-fault, fault and post-fault times[3]. Through the use of certain algorithms, the distance to the fault can be calculated. The designers claim a 3% error in distance calculations. The longer the length of the line, the bigger the stretch that has to be inspected in case of a permanent fault. The accuracy of these devices is not satisfactory to some power companies.

This thesis investigates a new way of fault location which would point out the faulted pole. This scheme will prove effective in greatly minimizing the time needed to locate the damaged pole via a communication system that sends the faulted pole's address when a fault takes place.

The Principles of the Fault Location System (FLS)

A few key words have to be clarified as to the particular meaning they have in this thesis. The word "fault" is used to describe any line to ground and line to line arcing occurring on the transmission pole structure, and not at the mid-span of poles. The word "pole" is used to describe any overhead transmission line support.

The FLS has the following criteria:

(i) Detection of a line to ground fault occurring on the pole by sensing currents in the static wire.

(ii) Detection of a line to line fault by sensing the electromagnetic fields produced by the arc on the pole.

(iii) Relay pole address or location code via transmitters and repeaters to a central control room.

(iv) Conduct a self-test of the repeaters involved in the code transmission every 24 hours.

CHAPTER 2

PRINCIPLE OF DETECTION

The Transducers

The line to line fault on a pole usually takes the form of an arc. The arc's magnetic field can be detected using an air core coil. The coil is positioned beneath the three phase conductors on the pole and is directed in such a way that the field produced by the arc, cuts through the plane of the coil. In this orientation, the plane of the field produced by the phase conductors is perpendicular to the plane of the coil. This will also assure that transients on the lines will have a negligible effect in the coil.

The voltage induced in the coil is given by

$$V_{ind}=4.4FANB \tag{2.1}$$

where F is the line frequency in Hz, A is the area of the coil in square meters, N is the number of turns and B is the magnetic flux density in Webers per square meter.

The magnetic flux density is calculated using

$$\overline{B} = \mu \, \overline{H} \tag{2.2}$$

where μ is $4\pi x10^{-7}$ and H is the magnetic field at the point of interest.

The magnetic field of an arc can be calculated using the magnetic field equation (2.3), of a finite length current-carrying conductor.

$$\bar{H} = \frac{I\bar{\phi}}{4\pi r}\left[\frac{b - z}{\sqrt{r^2 + (b - z)^2}} - \frac{a - z}{\sqrt{r^2 + (a - z)^2}}\right] \qquad (2.3)$$

where r is the perpendicular distance to the point of interest, I is the current flowing in the conductor, a and b are the conductor length limits on the coordinate axis, z is the distance to the perpendicular and ϕ is the direction of the H field as shown in Figure 1.

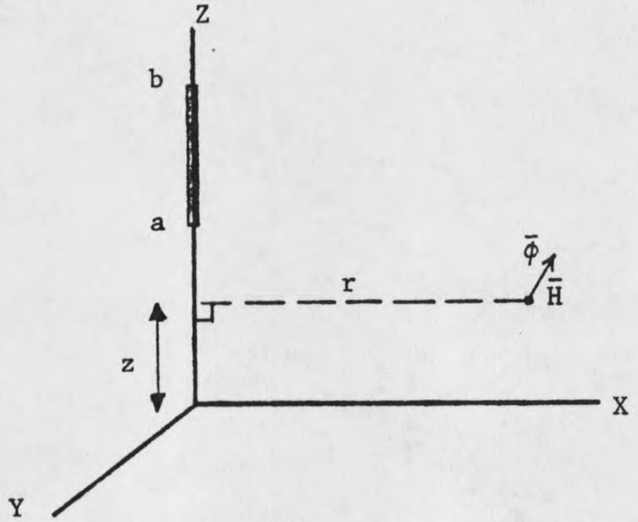


Figure 1.

Variables on the Coordinate axis for the

calculation of the magnetic field of a finite length of wire.

It is relevant to show that the effect of the sag of the conductors on both sides of a pole does not produce a significant field in the coil placed below the conductors. Figure 2 shows the direction of the phase currents in a sagging conductor. The conductors are shown as a straight line to simplify the analysis. If the field produced by segment AB is calculated at the coil's position using equation (2.3) there will be a component of that field that cuts the plane of the coil in the direction shown by the vector H' in the figure which is given by Hsinθ, where θ is the angle that the conductor makes with the horizontal.

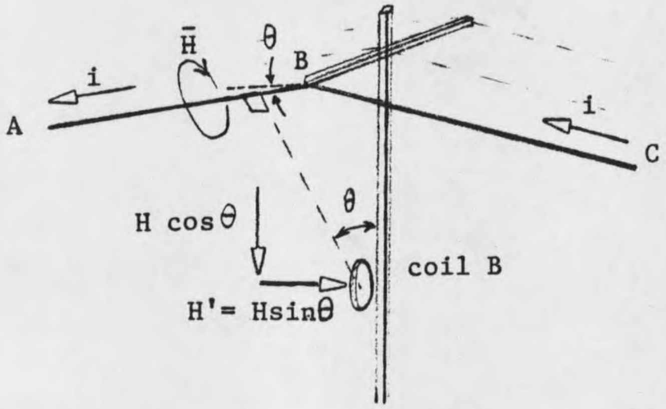


Figure 2.

Magnetic fields produced in coil by conductor sag.

The segment BC produces an H' component which is opposite in sign to the one produced by the AB member, therefore, canceling the effect of the H field in the coil.

The above statement will be true only if the plane of the coil was perpendicular to the field of the current carrying conductors and the sag in the conductors was equal on both sides of the pole. A complete cancellation of the field therefore cannot be achieved resulting in a very small voltage induced in the coil termed as noise.

The signal produced in the coil by an arc due to a line to line fault is significantly bigger than the noise present. Figure 3 and 4 show the voltage levels in the coil due to noise and that of a line to line fault respectively.

To conduct the experiments for this thesis, a model of a transmission line was built in Ryon Lab at Montana State University. The model was a 16:1 scale of a 161 kV transmission line used by Montana Power company. The model had a distance of 28 centimeters between the phase conductors and an insulation length of 8 centimeters. The line was energized with 110 V and had a balanced 50A/phase load. The coil for the line to line fault detection was placed 20 centimeters below the conductors. The coil had a diameter of 5 centimeters and 300 turns of 22 gauge insulated copper wire.

Induced voltages in the coil during a fault are relatively easy to find experimentally. A general observation of these types of faults indicate that fault currents can reach as high as 10 to 20 times the load current of the line and as low as that of the load current itself.

More graphs of induced voltage levels during line to line faults are shown in Appendix A.

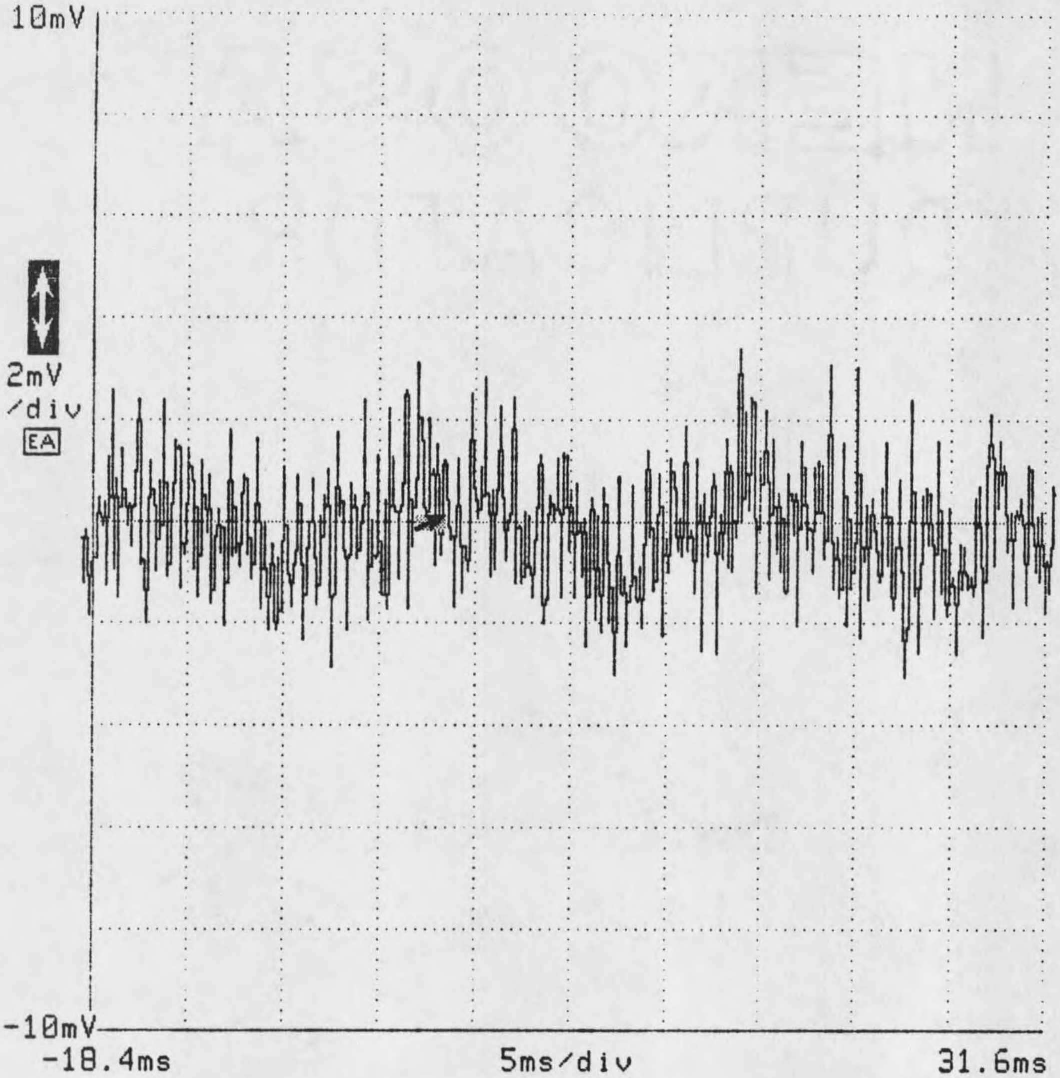


Figure 3.

Noise level in coil.

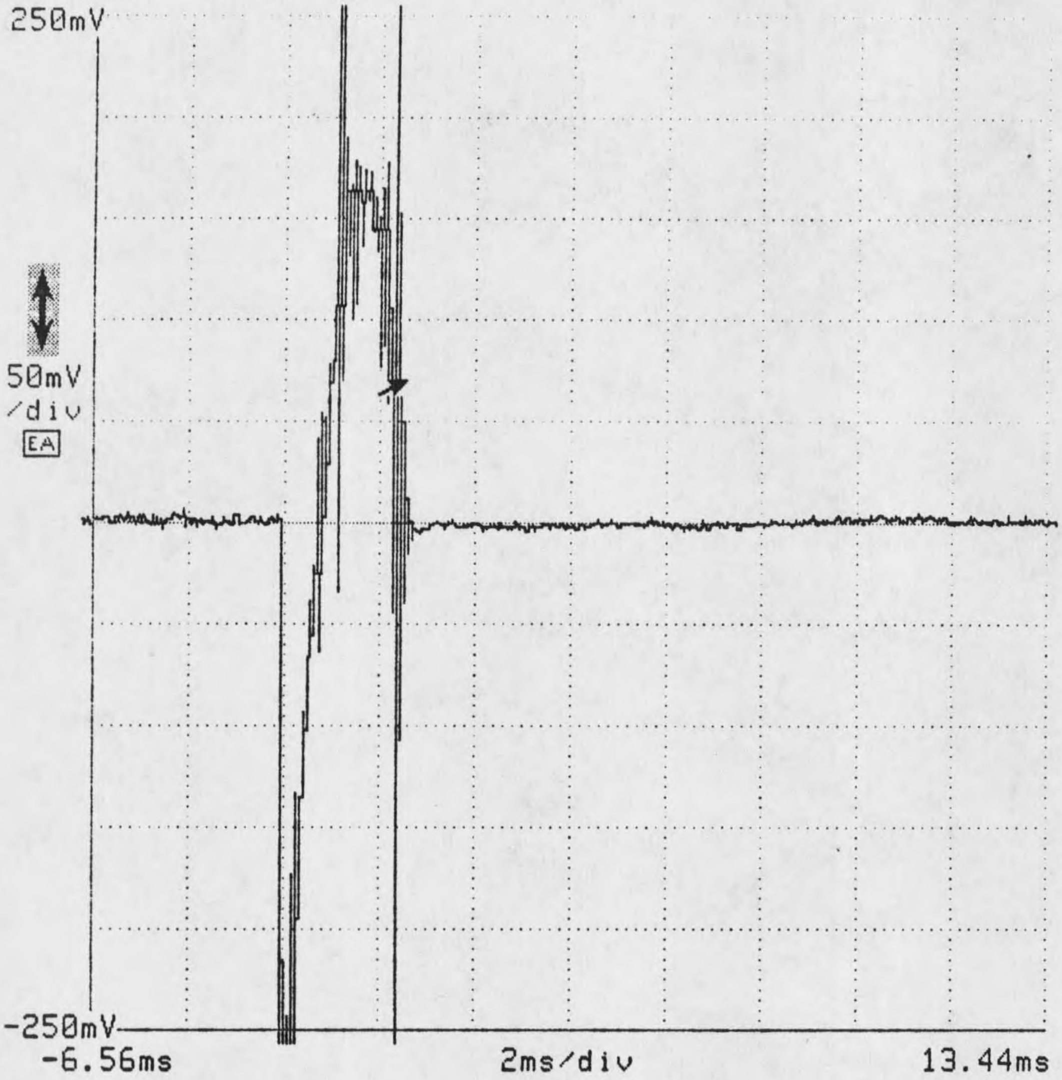


Figure 4.

Fault signal in coil due to arc

Transducers of a line to ground fault detection scheme are composed of two iron-core coils, one on each side of every pole, on the static wire. During a line to ground fault, the fault current that flows in the static wire splits both ways away from the pole as shown in Figure 5.

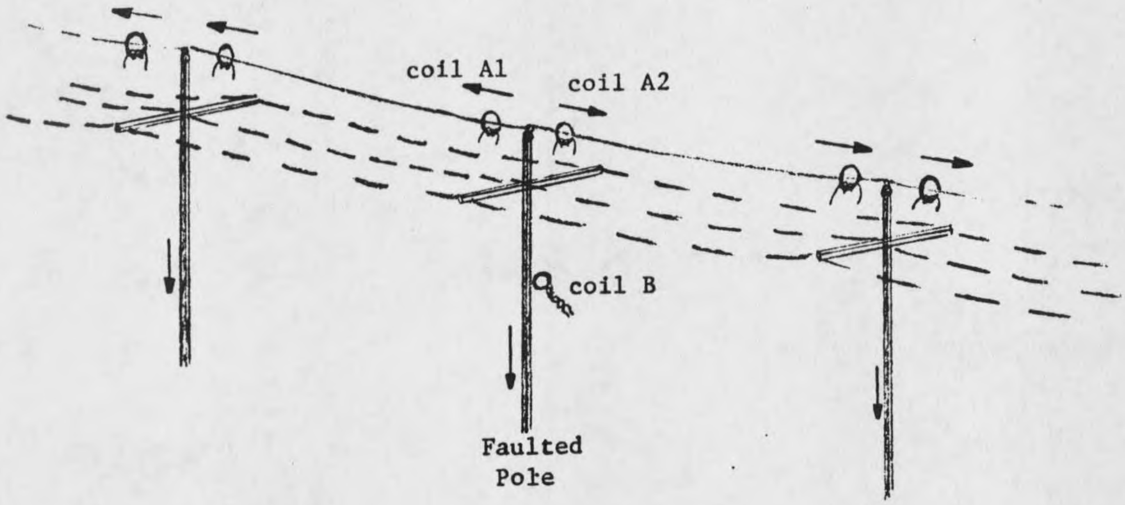


Figure 5.

Coil arrangement and direction of ground currents

during line to ground fault

The ground wire on the pole also has a portion of the fault current, but it is irrelevant to the detection scheme. When a line to ground fault takes place on the pole, the signals produced in the coils A1 and A2 may not be of equal magnitudes, but are out of phase. This is due to the unequal ground resistance seen on each side of the pole. One span away from the faulted pole the ground fault currents are flowing in the same direction through the next pole's set of coils. The signals in this situation are in phase with each other.

The voltage induced in the iron core coil is given by equations (2.1), (2.2) and (2.4).

$$\bar{H} = \frac{I\ \bar{\phi}}{2\pi r} \tag{2.4}$$

where r is the average radius of the toroid core in meters and μ in equation (2.2) is the permeability of the core material. In equation (2.1), A is the cross-sectional area of the core in square meters. Equation (2.4) is the limiting case of (2.3) where $b \rightarrow \infty$ and $a \rightarrow -\infty$.

The magnitude of line to ground currents in the static wire are not accurately predicted since they depend on the static wire's resistance on both sides of the pole. The fault currents stemming from an arc across an insulator can reach as much as ten times the load current. The minimum induced voltage in the coils can be estimated by the minimum amount of current flowing in the static wire. This current is a portion of the load current. This will give an idea of the minimum detection threshold required. This threshold is needed for amplifier gain consideration.

Consider an iron core cross section area of 25×10^{-6} square meters, an average core diameter of 4 centimeters, an initial permeability for iron of 500 and 80 turns of wire on the core. If a current of 25 amps is flowing in the static wire, it will induce 65 millivolts.

Line to ground faults were conducted on the same transmission line model mentioned earlier. Several fault waveforms are included in Appendix B.

The Instrumentation

Throughout the rest of this thesis, the coil associated with the detection of a line to line fault is termed as coil B. The two coils on the static wire associated with the detection of line to ground faults are termed as coil A_1 and coil A_2 as illustrated in Figure 5.

The signal in Coil B is amplified 500 times using a high input impedance amplifier followed by a gain stage. A comparator follows with a variable threshold. A 555 timer is used after the comparator in a monostable configuration which is triggered if a fault signal exceeds the threshold voltage level of the comparator. Coils A_1 and A_2 are connected to their individual amplifiers with a gain of 50. The amplifier outputs are then limited by 3.3V zener diodes. A summing (inverting) amplifier in an integrating configuration will add the two signals and integrate them over a desired period of time. LM741 Operational Amplifier are used for the instrumentation. During a line to ground fault on the pole, the signals generated in the coils are of opposite phases. The coil leads are connected in such a way that both coils display the same phase at the input of their amplifiers. This results in the signals adding constructively in the summing stage. On the other hand, the coil signals on the adjacent pole will be of opposite phase, therefore, canceling each other in the summing amplifier. The integrator time constant is useful in case of delays between the signal in coil A_1 and A_2. These delays will not allow proper cancellation of two out of phase signals, resulting in spikes as shown in Figure 6.

It is relevant to mention at this point that the signals induced in the two coils may be slightly different in shape and magnitude also. This will not result in a total cancellation of two out of phase signals. In the last two cases, the time constant is set large enough to allow no appreciable signal level at the output of the integrator. Therefore, the comparator circuit following the integrator will set the threshold desired for the decision boundary. Figure 7 shows the detection coils and their respective instrumentation.

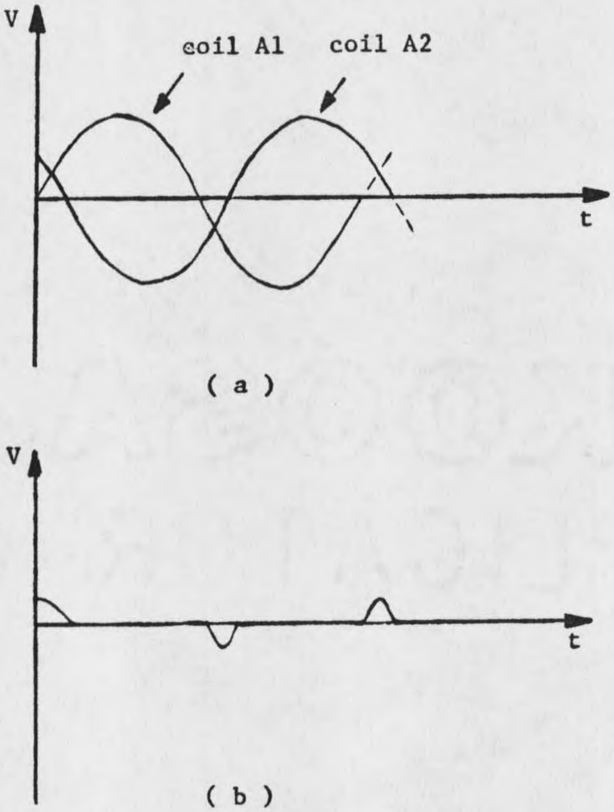


Figure 6.

(a) Delayed signals (b) Summing output

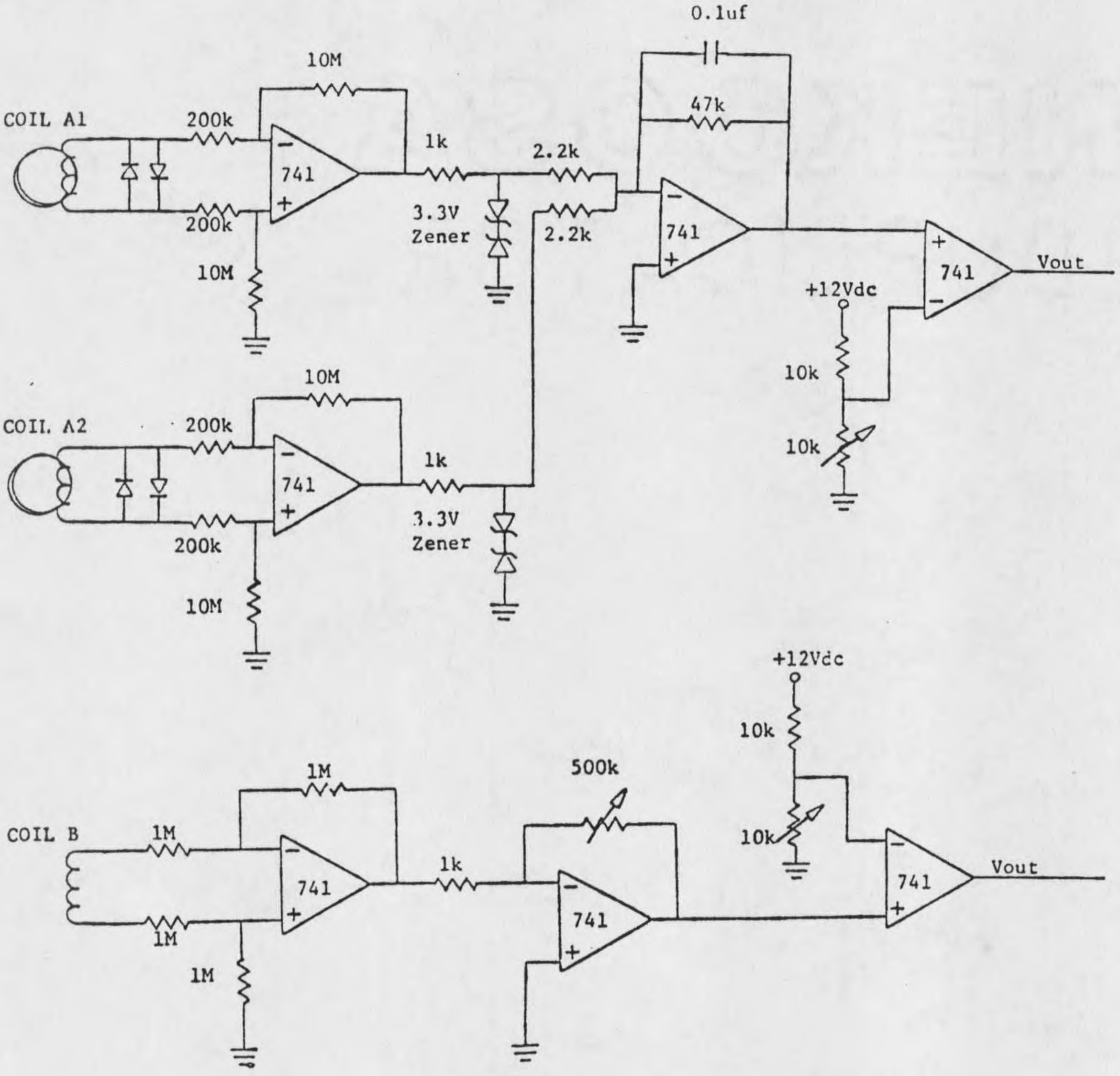


Figure 7.

Detection instrumentation

The Decision Logic

Four signals make up the inputs to the logic circuitry for decision making. All four inputs come from 555 timers. The inputs to the timers are amplifier outputs of coil A_1 and coil A_2, comparator output of coil B and the comparator output of the summing amplifier. The reason for using the timers is to prolong the duration of the comparator outputs and to sustain the decision of the other outputs long enough for proper logic processing. The timers operate as monostable multivibrators with a $\tau = 0.5$ second.

The decision for declaring a fault is based upon the following criteria.

For a line to ground fault:

(i) Coils A_1 or A_2 must have a signal present in them.

(ii) The output of the summing amplifier's comparator must be positive. (This signifies that the signals add constructively which is an indication of a fault taking place on that particular pole.)

(iii) Coil B's signal is irrelevant.

For a line to line fault:

(i) Coil B's signal must exceed the comparator threshold.

(ii) Coil A_1 and A_2 should not have any signals in them.

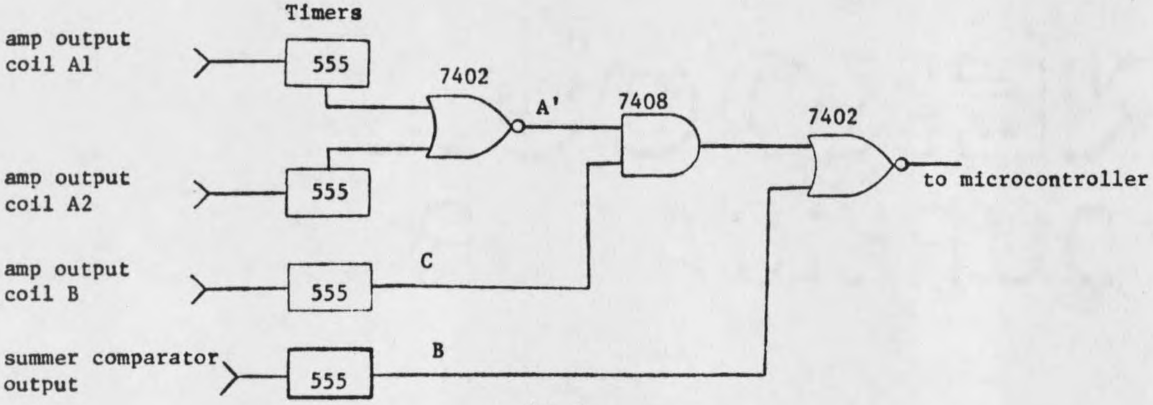
(iii) the summing amplifier's comparator signal is irrelevant

If signals are present in all three coils and the output of the summing amplifier's comparator is negative, this indicates a line to ground fault on an adjacent pole in which case the logic would not "declare a fault". Figure 8 shows the truth table and the logic circuit for the decision making.

The output of the logic circuit at the time of a fault will give a negative edge pulse. This pulse is needed by the microcontroller as an Interrupt signal for code transmission. The pulse duration is about 0.5 second which exceeds the needed 3µ second of the microcontroller.

A' B C	00	01	11	10
0	0	1	1	0
1	1	1	1	0

(a)



(b)

Figure 8.

(a) Truth table. (b) Decision Logic circuitry

CHAPTER 3

TRANSMISSION OF POLE IDENTITY

Transmitting the data that contain the pole address is done via a microcontroller(MC), a modem, a transmitter and repeaters. A brief description of these units and their function in transmitting the data is included in this chapter.

Each pole is given a 16 bit code which specifies its position between two repeaters. The first 12 bits are the actual address of the pole and the last 4 bits are all set high by the MC to distinguish a pole code from that of a repeater's. The 12 bit code is entered using 12 microswitches. The MC used is an Intel 8751 which processes the code for transmission. The program stored in its EPROM executes the following functions:

(i) Upon receiving an interrupt from the decision logic, the MC reads the microswitches that have the pole address. It utilizes 2 I/O ports for this function.

(ii) The program introduces a delay of 1.4 seconds before it sends the code 3 times in a row (6 bytes) to its serial port. One second delay is introduced to prevent any magnetic fields present around the pole during a fault from interfering with the code transmission. The remaining 0.4 second delay is needed by the receiving modem to lock in the carrier of the transmitter.

(iii) After the code is sent out to the modem, the MC ignores any interrupts from the decision logic until a second transmission is completed 5 minutes later.

(iv) After the previous step, the MC is ready to process another data transmission.

An MM74HC943 300 Baud Modem is used to modulate the 49.8 MHz transmitter. It uses frequency shift keying of audio frequency tones. It can operate at two sets of frequencies (Answer/Originate). The digital code out of the microcontroller is translated into the designated frequency allocations according to Table 1. This is done by setting the A/O pin on the modem Low or High respectively.

Table 1.

Frequency Allocation of the MM74HC943 Modem

Data	Originate Modem		Answer Modem	
	Transmit	Receive	Transmit	Receive
Space	1070 Hz	2025 Hz	2025 Hz	1070 Hz
Mark	1270 Hz	2225 Hz	2225 Hz	1270 Hz

The modem in this application will be used as a modulator only. The transmitter used for sending the code is a TRC-501 49.8 Mhz FM transceiver made by Realistic with 100mW of power. The modem's modulating signal is tapped into the transmitter circuit of the transceiver.

The repeaters are located within the transmitting power range of the transmitter units (A range of approximately 2 miles of transmission was observed under the transmission line is used by the Montana Power Company).

The repeater is made up of a 49.8 MHz transceiver, a modem and a microcontroller. The modem and the microcontroller are the same chips used in the detector/transmitter units. The modem in this application is used in full duplex mode; where it transmits and receives digital data from the MC and also modulates and demodulates the FM signals of the transceiver.

The repeater's MC has the following functions:

(i) Data from the transmitters are checked for errors among the three codes (2 bytes each).

(ii) The MC regenerates the code and send it to the modem for transmission.

(iii) The MC powers on the transmitter for 0.4 seconds before it sends the code through the modem. (The delay here is again one needed by the next repeater's modem to lock in the carrier frequency sent by the transmitter.)

(iv) The MC will not process any data for a period of 2 minutes to prevent the looping of data between itself and adjacent repeaters.

(v) The repeater, at one end of the line, transmits a code every 24 hours as a test for the entire repeater link. In case a code is not received by a repeater after the 24 hour time limit, it will transmit its own address. (This will indicate that the previous repeater is malfunctioning.) The repeater's address is an 8 bit code, which is set in the unit via 8 microswitches on the MC's I/O port. Figures 9 and 10 show the schematics for the transmitter and the repeater circuits respectively.

The Transmission Network

Each pole has its own detector/transmitter unit where the modem can be set to either Originate or Answer mode. Each set of transmitters between two repeater sites carries one or the other mode of operation. Only one of the two repeaters can respond to this set of transmitters since its modem is set to either Answer or Originate mode also. Therefore, the transmitted code propagates in one direction. Figure 11 shows a block schematic of frequency assignments. To help clarify the assigned transmitting and receiving frequencies of each unit , assume that the Originate mode transmits at f_1 and receives at f_2 while the Answer mode transmits f_2 and receives f_1.

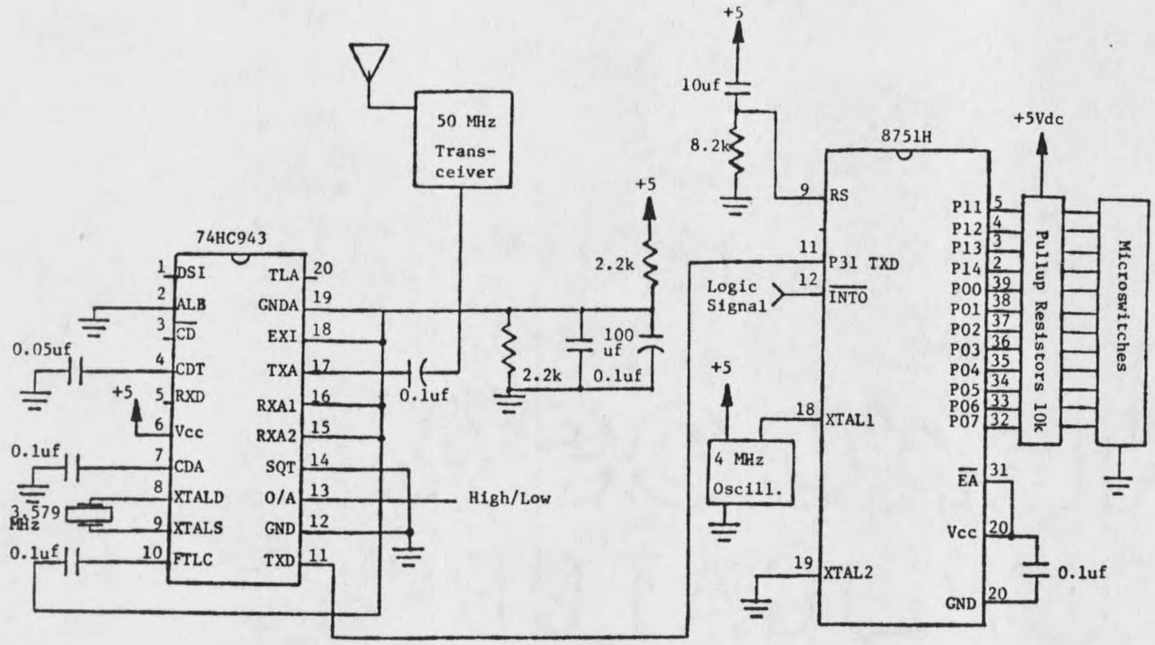


Figure 9.

Schematic of Transmitter Circuitry

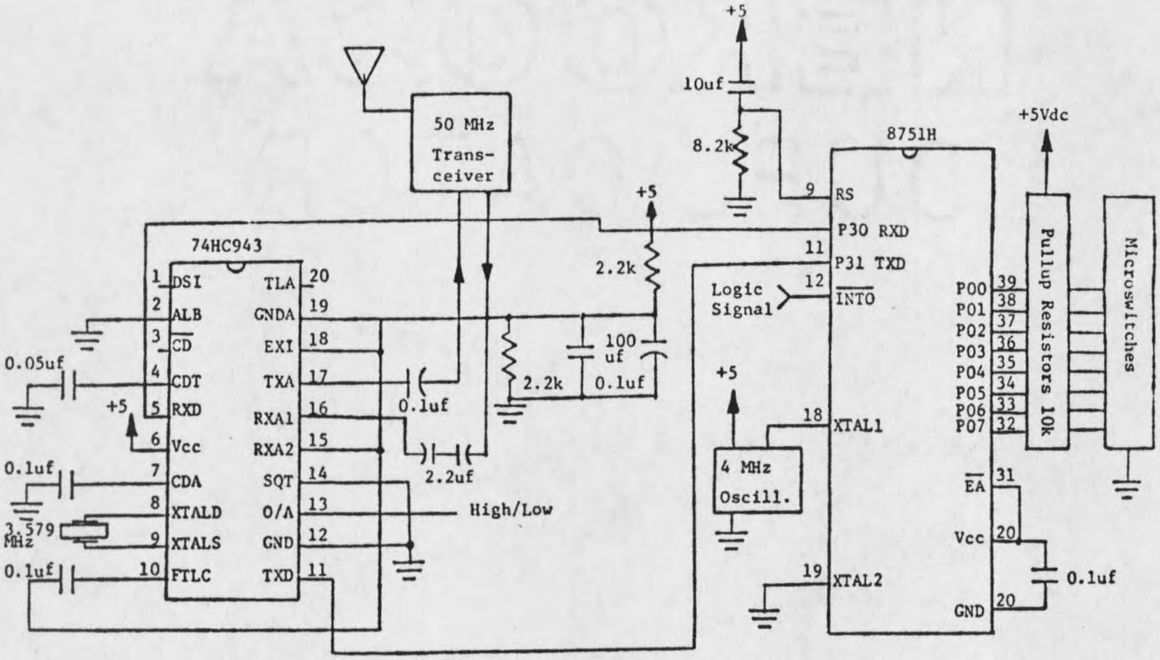


Figure 10.

Schematic of Repeater Circuitry.

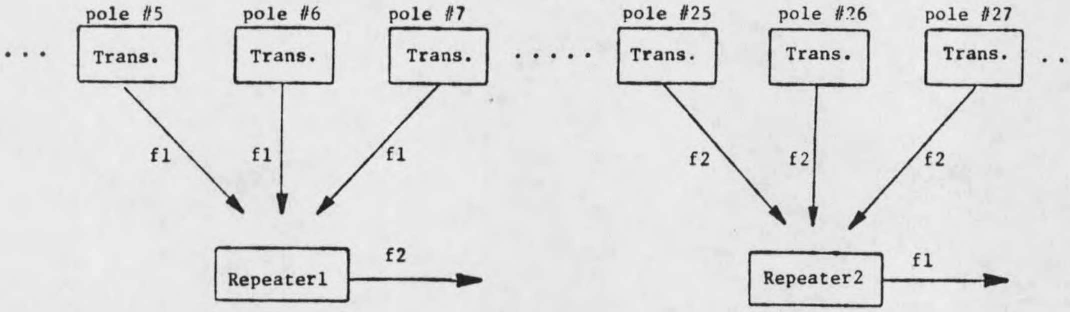


Figure 11.

Code-Transmission Network

Error Correction

There is no elaborate error correction scheme involved at the repeater sites. The three (6 byte) codes undergo a bit by bit check. In case of an error in one of the positions, the two bits of the other two transmissions make up the decision for that bit position. For example the code of the third transmission shown has an error in one of the positions,

0111 0111 0111 1111

0111 0111 0111 1111

0011 0111 0111 1111

the MC will then retransmit the following code

0111 0111 0111 1111

The code is received at a designated control room or substation. The receiving device for this FLS for determining the code sent, consists of a receiver and a modem. Upon receiving a code transmission, the modem displays the code on a Storage Oscilloscope. A personal computer based system can be used to receive and store these codes.

Experimental Results

To test the validity of the FLS, in detecting line to line and line to ground faults, a series of experiments were conducted on the transmission line model mentioned earlier.

The line to line and line to ground faults were performed by throwing 20 gauge wire on the conductors. The fault duration of these faults was about 2-5 milliseconds depending on the fusing time of the wire or the circuit breakers in the laboratory. The voltages induced in the coils are shown in Appendix A and B. The threshold of the comparator on coil B was adjusted to prevent any noise from triggering the logic. The threshold of the summing amplifier's comparator was adjusted so that the remaining voltage signal after the cancellation of two out of phase waveforms, would not trigger the logic.

The adjustments were performed after a series of faults was conducted on the line. It can be seen in appendix B that on the pole adjacent to the faulted one, the signals in the coils are not always of the same shape. Therefore the resulting output of the summing amplifier will always have different magnitudes.

The code transmission was checked by entering different codes on the microswitches and comparing them to the received code on the storage oscilloscope. Only one repeater was used in the testing of the communication link.

The experiments for the FLS were conducted in a laboratory environment. No experiments, were conducted on outdoor transmission lines.

CHAPTER 4

CONCLUSION AND FUTURE WORK

A new fault location scheme has been presented. The system detects line to line faults by sensing the magnetic fields emitted from the arc. Line to ground faults on the pole are detected by sensing the current phase differences in the static wire on both sides of the pole. By monitoring the outputs of the sensing coils, the decision logic determines if a fault has occurred on the pole or not. When a fault occurs the microcontroller in each unit reads the address of the pole from a set of switches. It then sends the code three times in a row to the modem, with the proper delays needed by the receiving devices. A 49.8 MHz transmitter relays the modulated code to a repeater. The repeater checks the code for errors and retransmits it to the next repeater and so on till it reaches the desired location. A 24 hour check is done by the repeaters to assure proper functioning of the repeater links.

Suggested future work on this Fault Location System involves

(i) power supply considerations for outdoor use

(ii) minimizing the analog instrumentation involved in the detection circuitry by incorporating more digital signal processing.

(iii) introduce a 24 hour check on the pole sending units.

(iv) incorporate 900 MHz transceiver for more efficient transmissions.

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APPENDICES

APPENDIX A

LINE TO LINE FAULTS

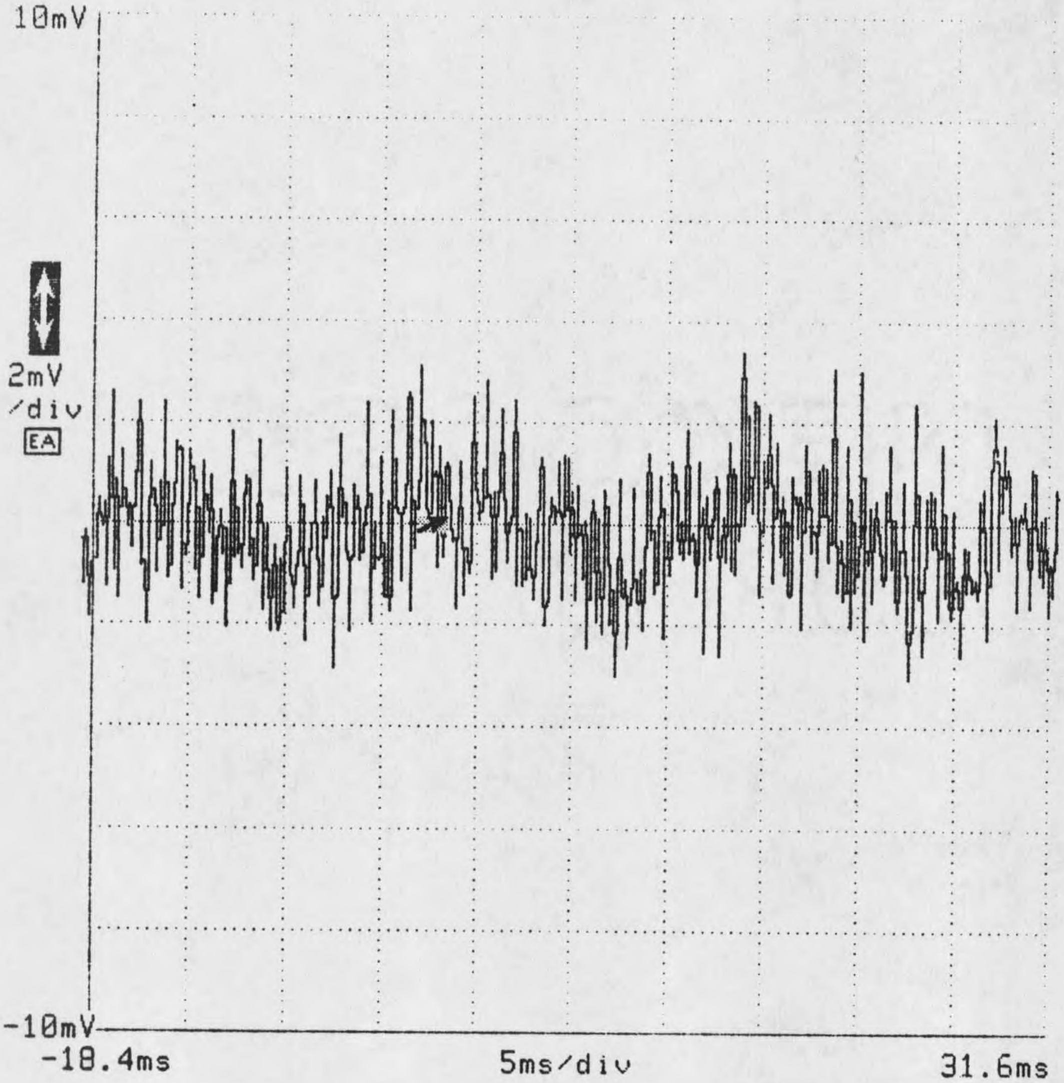

Figure 12. Noise signal in coil B.

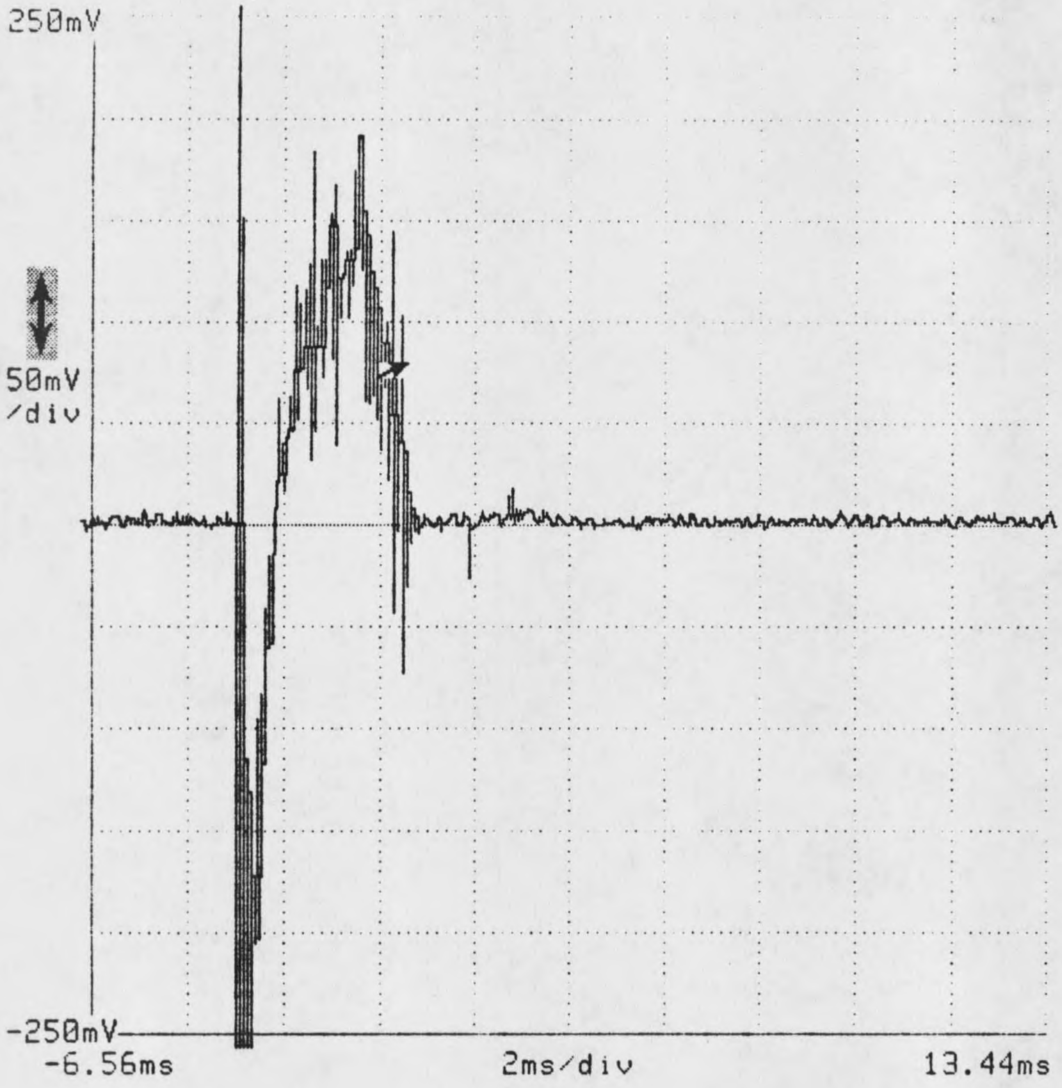

Figure 13. Line to line fault signal in coil B before amplification.

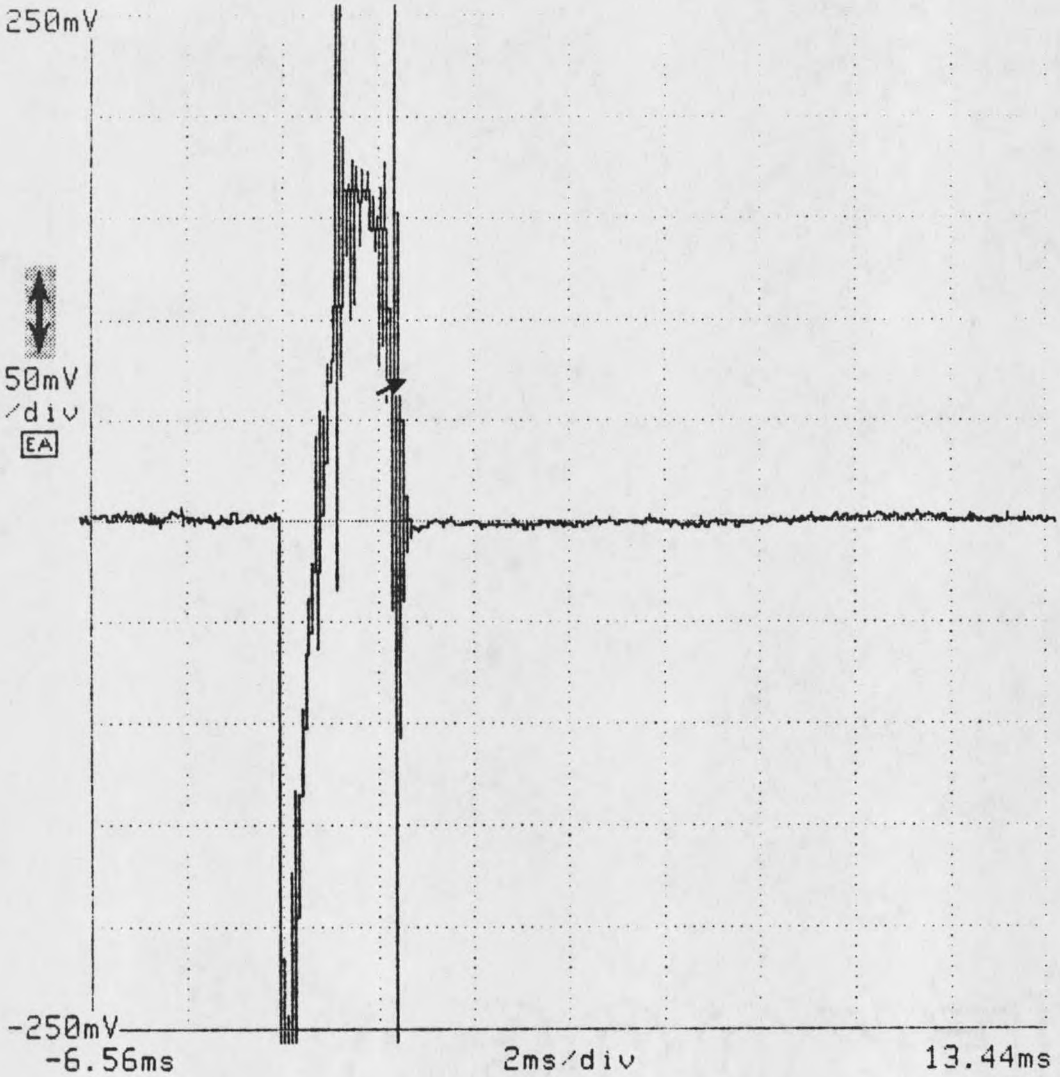

Figure 14. Line to line fault signal in coil B. Note the difference between this signal and the one shown in Figure 13.

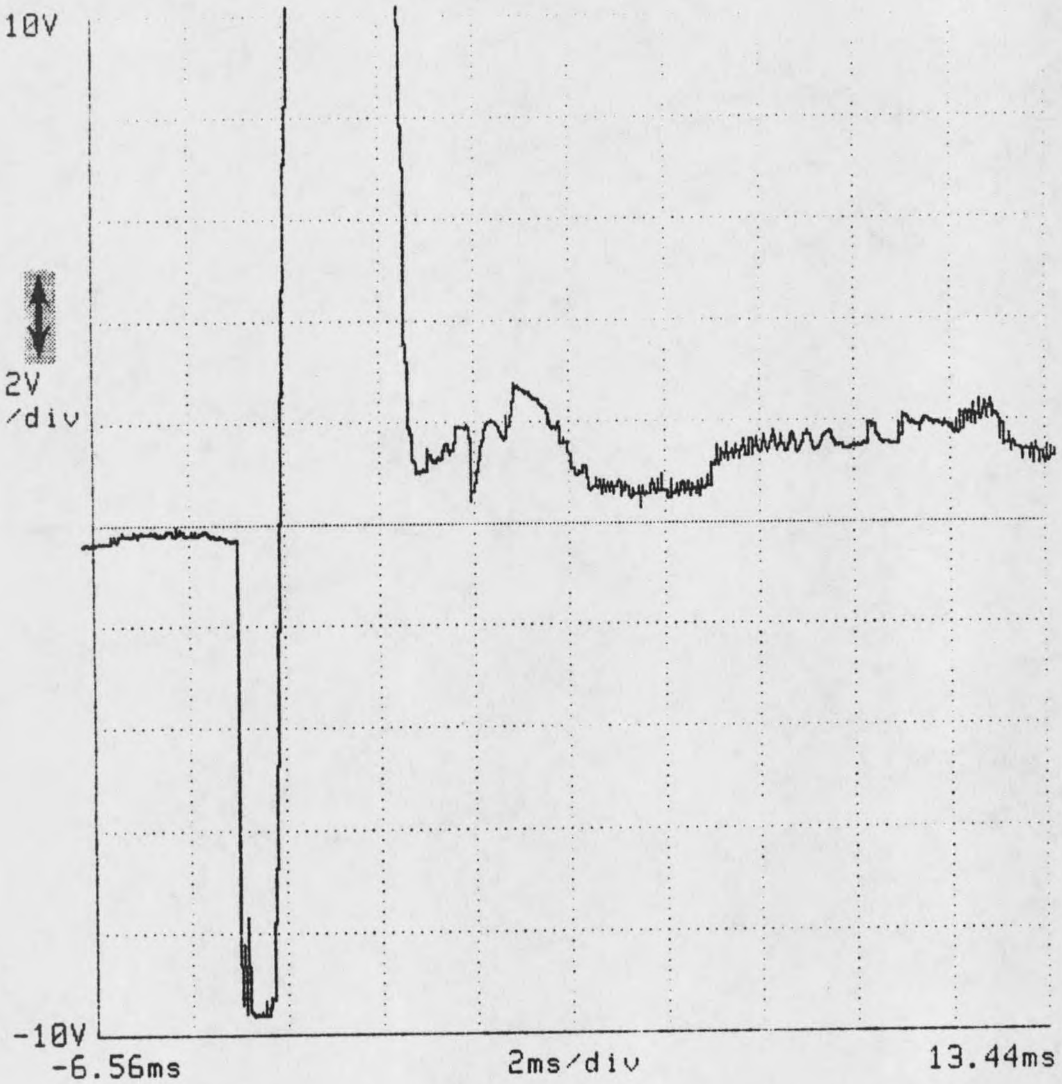

Figure 15. Coil B's amplifier output (gain=500). This is the amplification of the signal in Figure 14.

APPENDIX B

LINE TO GROUND FAULTS

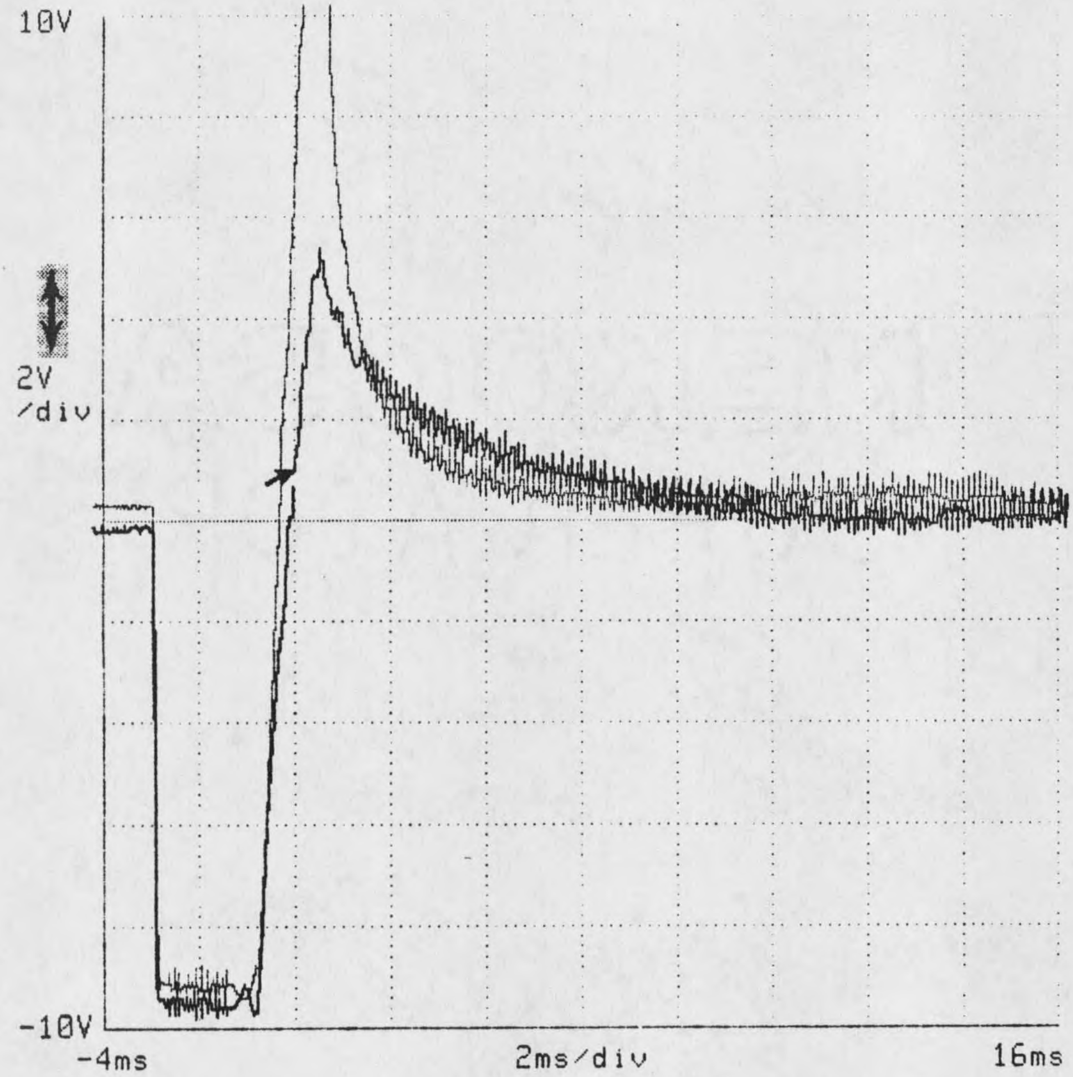

Figure 16. Voltages induced in coils A1 and A2 at the output of their amplifiers (gain=50). Note the signals are in phase.

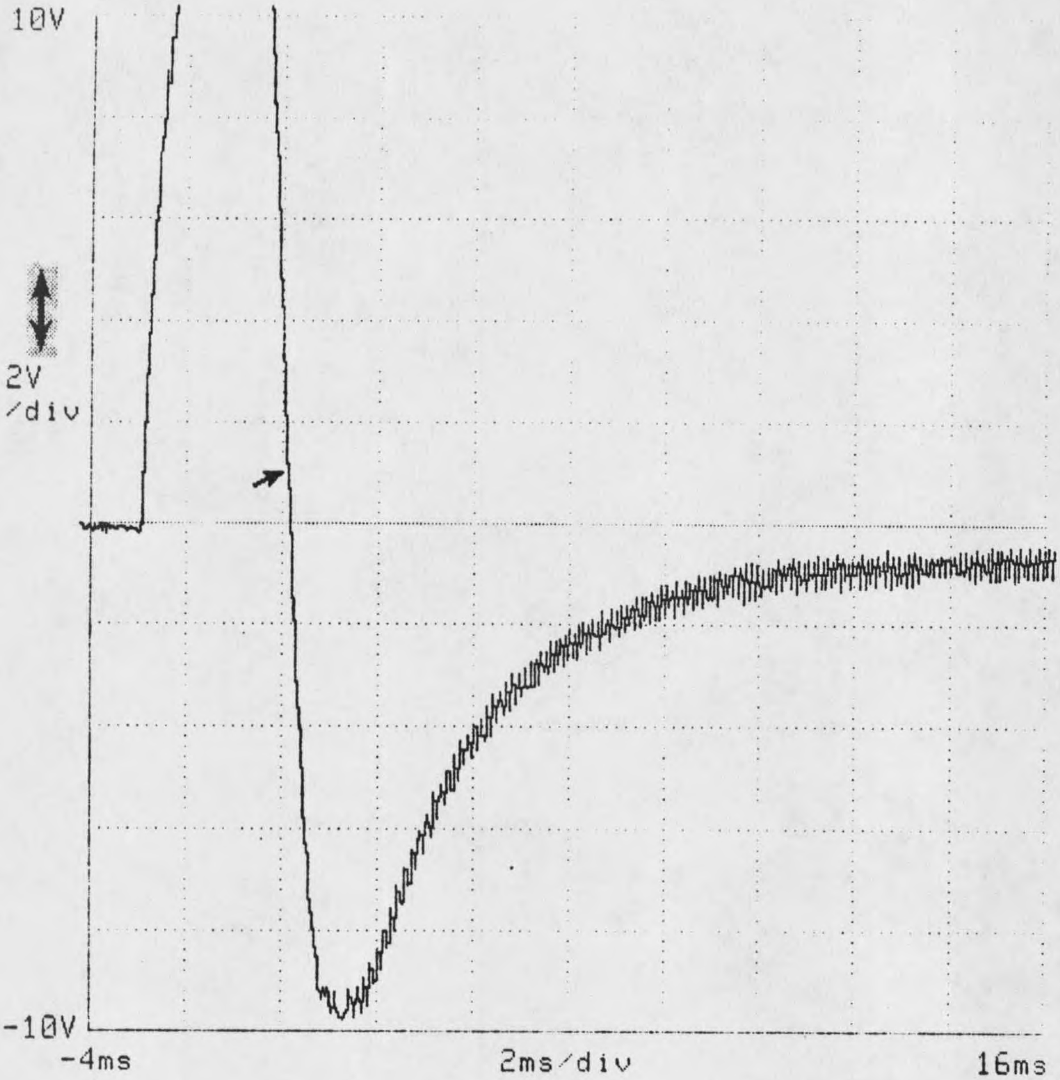

Figure 17. Voltage signal at the output of the summing amplifier of the two in-phase input signals of Figure 16.

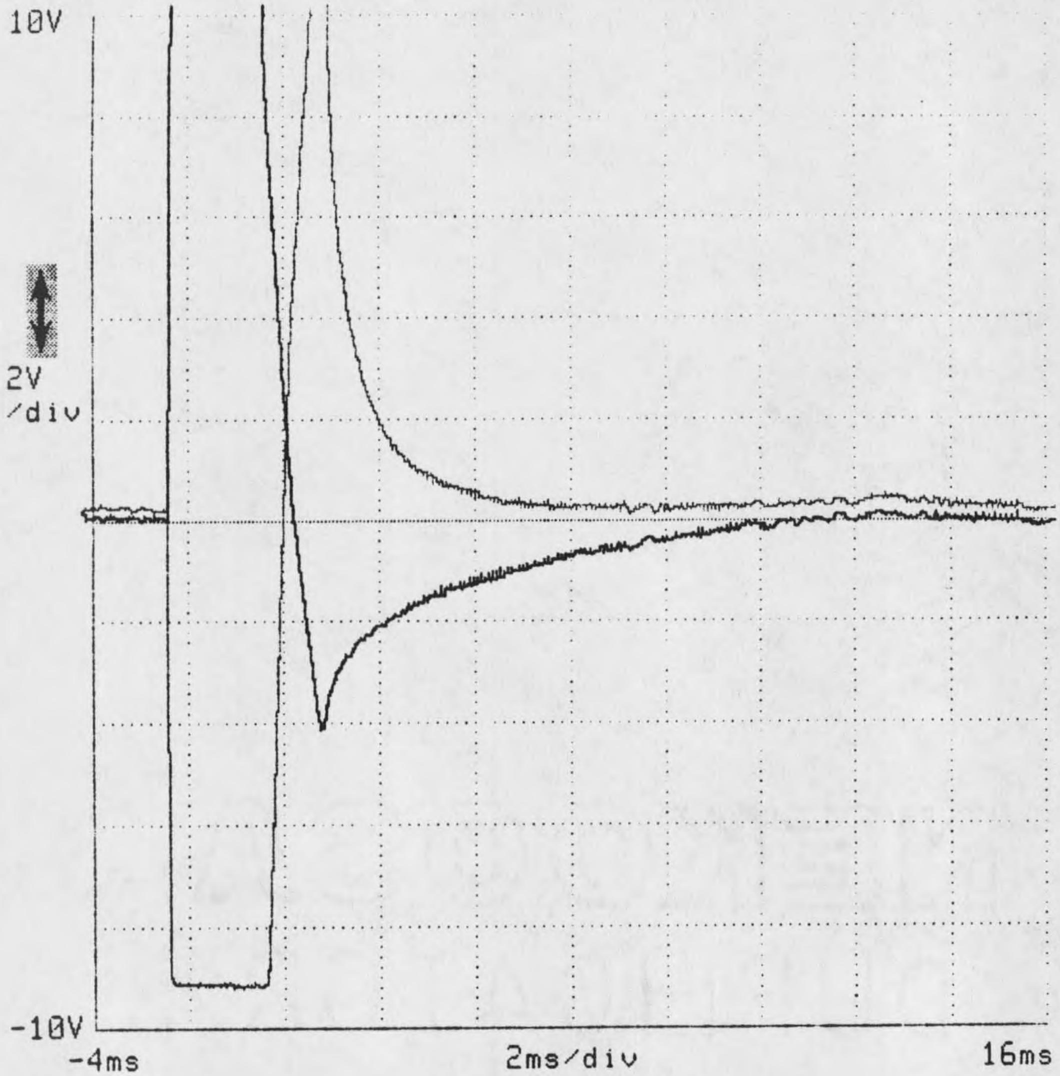

Figure 18. Voltages induced in coils A1 and A2 at the output of their amplifiers (gain=50). Note the signals are out of phase.

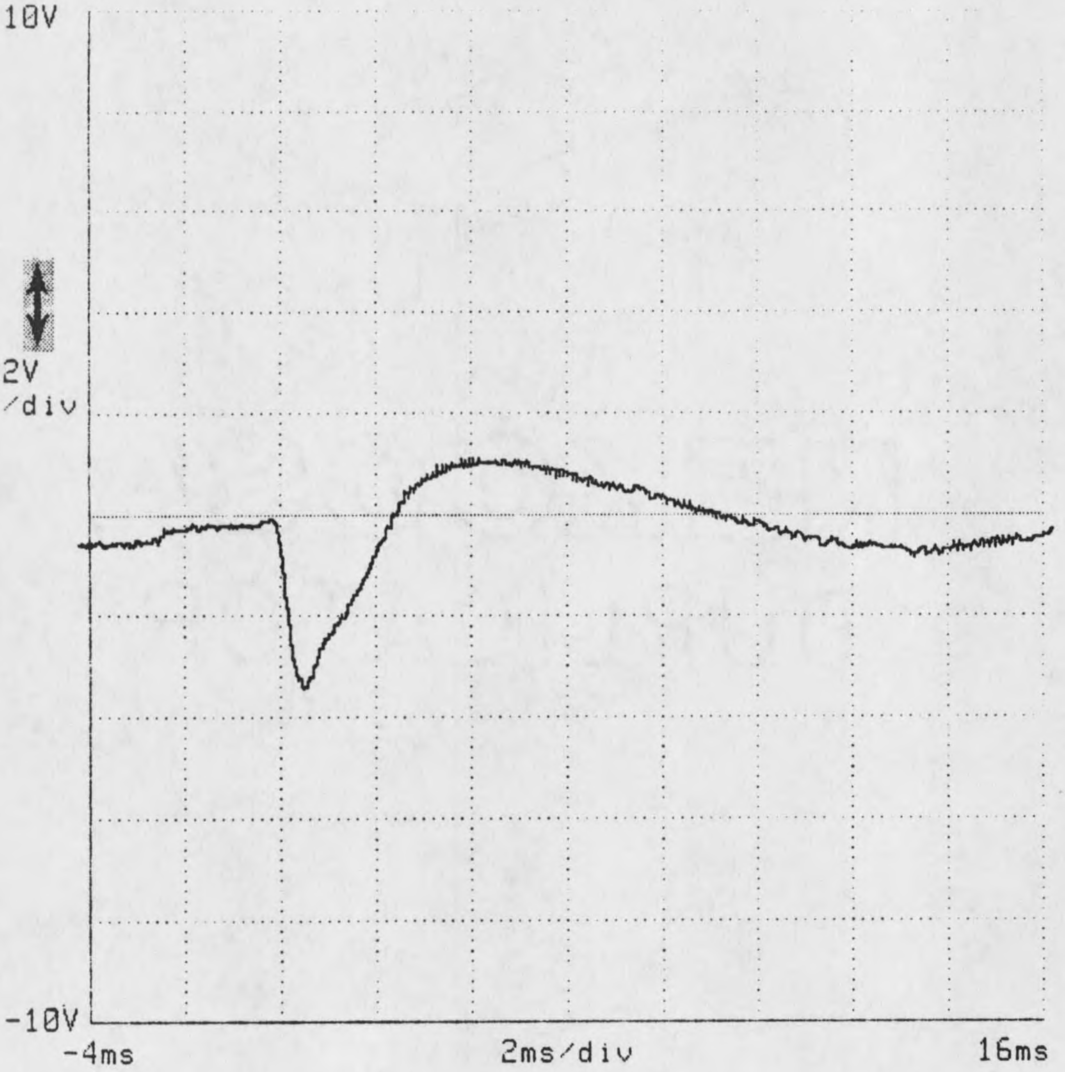

Figure 19. Voltage signal at the output of the summing amplifier of the two out of phase signals of Figure 18.

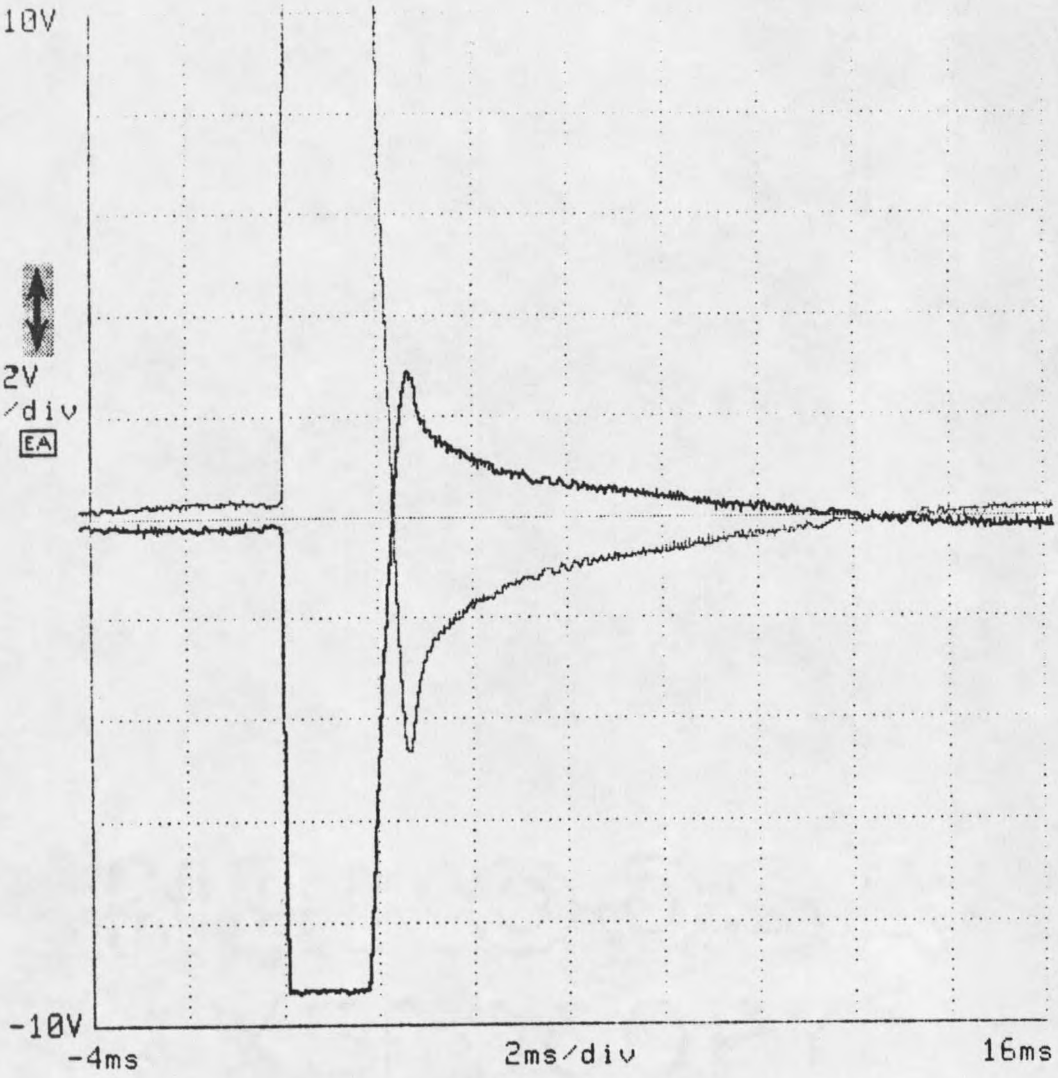

Figure 20. Out of phase signals induced in coils A1 and A2, showing a different shape and magnitude than the ones shown in Figure 19.

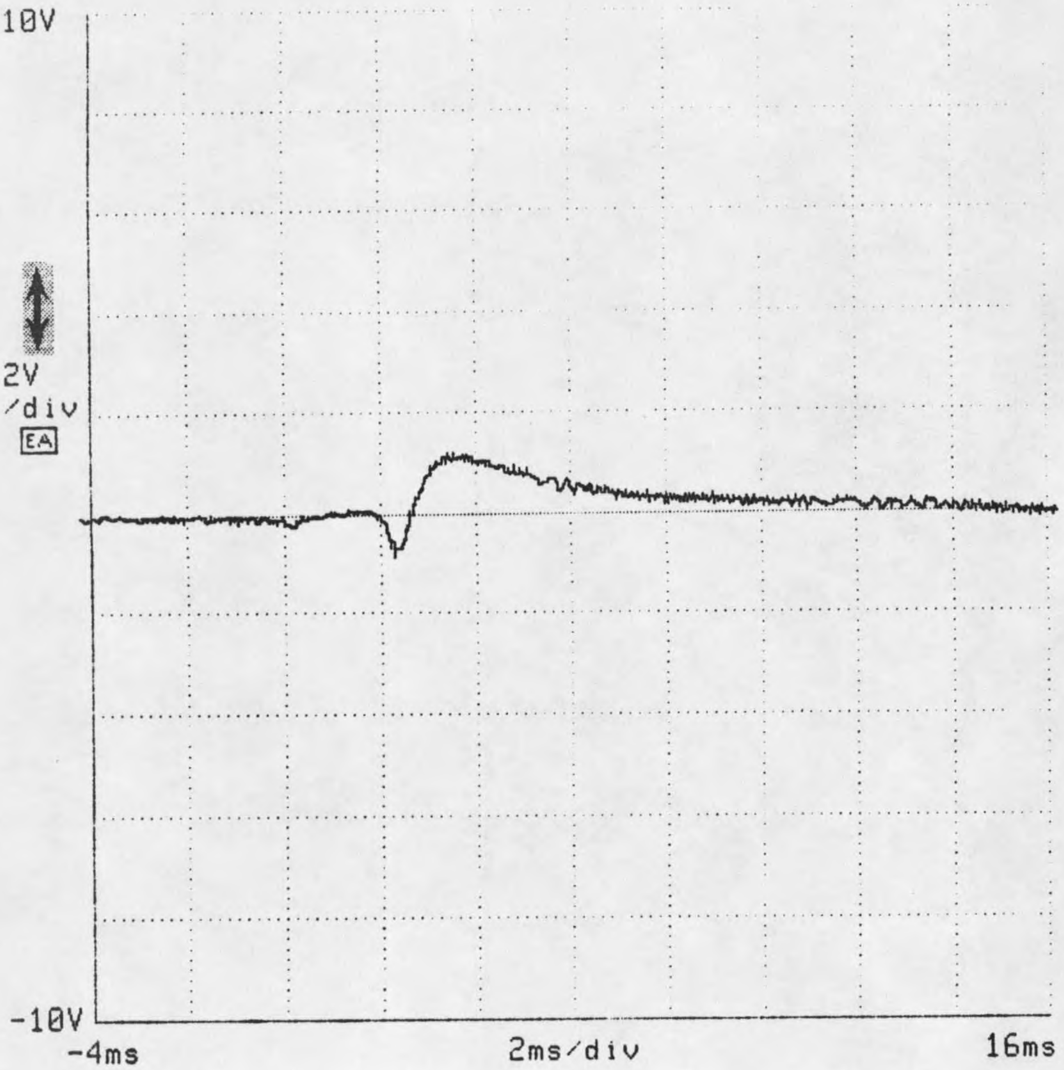

Figure 21. Summing amplifier output of the signals shown in Figure 20.