Power transmission line fault location system

by Mark Edwin Lund

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

Abstract:
Power companies want to minimize power outage time since it is an inconvenience to customers and results in lost revenue. The time it takes to restore power after a fault depends upon quick and accurate fault location. Errors in fault location distance from ten to twenty percent of line length are common with the existing methods.

This thesis demonstrates the feasibility of a fault location system which detects and locates phase to ground and phase to phase faults at the supporting structures of an overhead power transmission line. A Fault Detector is placed on each tower of the transmission line. The direction of fault current in the static wire is used to determine fault location for transmission lines with grounded static wires. The magnitude of current flow in the tower is used to determine fault location for transmission lines with insulated static wires. When a fault occurs the Fault Detector at the faulted tower reports the fault location to a control room. Linemen are then dispatched to the faulted tower to correct the problem.

The feasibility of the fault detection scheme is demonstrated by the results of staged fault tests. Two types of Fault Detectors were built and tested. Both types of Fault Detectors were tested on a scaled model transmission line in Ryon Laboratory at Montana State University and on a low tension transmission line on the Montana State University campus. Additionally, the system detected and located staged phase to ground and phase to phase faults conducted on 100 KV and 115 KV transmission lines. A proposed 500 KV transmission line staged fault test is also outlined.

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Master of Science

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Electrical Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

January 1992

APPROVAL

of a thesis submitted by

Mark Edwin Lund

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date January 9, 1992

ACKNOWLEDGMENTS

The author is especially grateful to his thesis advisor, Dr. Murari Kejariwal, for his help and support during the course of this investigation. Appreciation is also extended to Dr. Daniel March and Dr. Baldev Thapar for their help and critical review of this manuscript.

This project was funded by the Montana Power Company and the Montana Electrical Power Research Association. A special thank you is offered to Mr. Eugene Braun of the Montana Power Company who made high voltage transmission lines available for staged faults to test the Fault Location System.

The writer is particularly indebted to his fellow students, Mr. Mark Welty and Mr. Stephen Gaub. The author also extends his most sincere appreciation to his wife, Judith, for her love and support.

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ABSTRACT

Power companies want to minimize power outage time since it is an inconvenience to customers and results in lost revenue. The time it takes to restore power after a fault depends upon quick and accurate fault location. Errors in fault location distance from ten to twenty percent of line length are common with the existing methods.

This thesis demonstrates the feasibility of a fault location system which detects and locates phase to ground and phase to phase faults at the supporting structures of an overhead power transmission line. A Fault Detector is placed on each tower of the transmission line. The direction of fault current in the static wire is used to determine fault location for transmission lines with grounded static wires. The magnitude of current flow in the tower is used to determine fault location for transmission lines with insulated static wires. When a fault occurs the Fault Detector at the faulted tower reports the fault location to a control room. Linemen are then dispatched to the faulted tower to correct the problem.

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CHAPTER 1

INTRODUCTION

Reliability of overhead transmission lines is a top priority of power companies. Customer outage results in lost revenue and disruption of service. If the fault is found quickly and accurately, the cause can more likely be determined.

Background

Traditionally, faults in overhead circuits are located by isolating sections and exposing the system to repeated close-ins. Linemen visually inspect the isolated sections for the fault. Helicopters are sometimes used to decrease the inspection time.

Fault indicators may be employed to help identify where the fault exists. One type of indicator placed on the static wire uses two magnets. Fault current demagnetizes one magnet causing a red flag to show. The flag is held in this position by the other magnet until a lineman resets the indicator. The trip current is set at the factory. Many of these indicators on towers on each side of the faulted tower may trip if the fault current is higher than the trip current rating. Also, none of the indicators may trip if the fault current is smaller than the trip current rating. Confusion may occur on the location of the present fault if all the indicators were not reset after a previous fault [1]. Other indicators of this type reset automatically after a specified amount of time.

Another type of indicator clamps directly around the high voltage conductor. It senses both line current and voltage. The simultaneous presence of line voltage and a stepped increase in current triggers the unit [2].

Faults can also be located by using traveling wave time intervals from the fault. Electronic clocks at each side of a line section record the exact time a traveling wave from the fault reaches its terminal. The fault is located by the incremental difference in time between the clocks. This method requires the clocks to be precisely synchronized. This is accomplished with a microwave link. A major source of error for this system is the variation in travel time over the communications link [3].

Another technique of locating faults is the Oscillograph and Fault Study Analysis Method. This method uses a model of the power system as fault study program data. A fault on the line section of interest is moved along the line (i.e. a sliding fault) until the magnitude of the current obtained from the fault study equals that measured on the oscillograph [3].

Schweitzer Engineering Laboratories has developed a relay, SEL-21, which provides fault location. The relay continually monitors voltage and current at one line terminal. Pre-fault and post-fault data are processed using the Takagi algorithm to determine the location of the fault [4,5].

Power companies want the location of the fault more accurately and sooner than these methods can provide. This thesis investigates fault location based upon direction of fault current in the static wire and also based upon magnitude of fault current in the faulted tower.

Fault Location System Design

This Fault Location System was designed based upon the following:

1. Determine fault location by

    i. direction of current flow in static wire for transmission lines with grounded static wires.

    ii. magnitude of current flow in tower for transmission lines with insulated static wires.

2. Factors such as power consumption and circuit optimization were given high priority.

3. Implement decision logic for identification of faults in software instead of hardware to increase accuracy. This also enables easy modification of the decision criteria.

4. Fault Detector on faulted tower transmits fault location by radio. Use an error correction code to increase the reliability of the transmitted information.

CHAPTER 2

FAULT LOCATION SYSTEM

Faults are classified into two types: phase to ground faults and phase to phase faults. Most faults, about 90 percent, are phase to ground faults. A phase to ground fault occurs when one of the phases is shorted to ground. A phase to phase fault occurs when either two or all three phase lines are shorted to one another. Faults are caused by insulator breakdown, fallen lines, foreign objects (e.g. trees hitting the lines), and other randomly occurring events. A phase to phase fault may also occur if high wind slaps the conductors together.

The system being developed locates phase to ground and phase to phase faults to the nearest support tower of an overhead transmission line. The system consists of Fault Detectors, Repeaters and a Control Room Monitor (Figure 1). A Fault Detector is installed on each tower of the transmission line. When a fault occurs the Fault Detector at the faulted tower transmits a message frame containing its unique Tower Identification Code. Repeaters relay the message frame to the Control Room Monitor at the power company's headquarters. The Monitor displays the Tower Identification Code of the faulted tower and other pertinent information.

The line configuration as discussed later dictates whether Type I or Type II Fault Detectors are installed. All the units on a single line must be of the same type. When a fault occurs the Fault Detectors near the fault are awakened by the fault

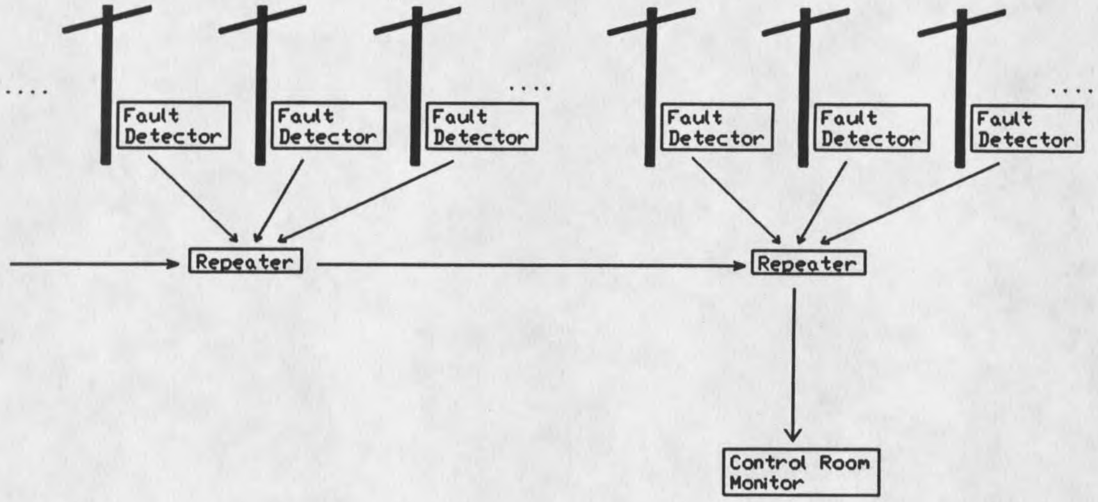
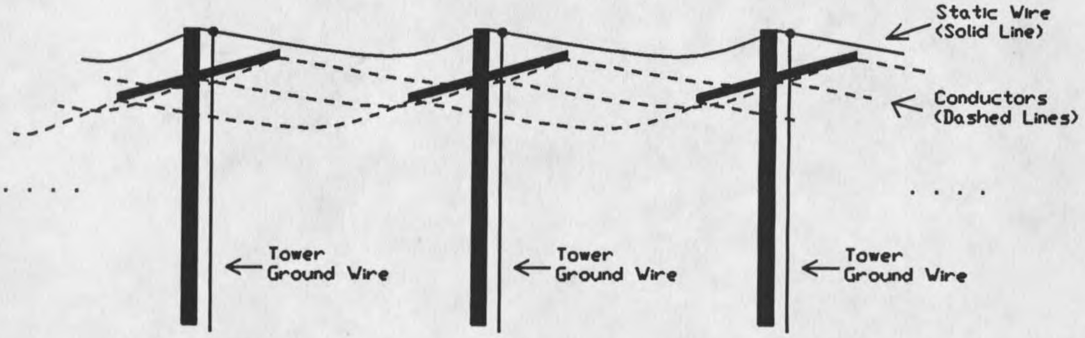
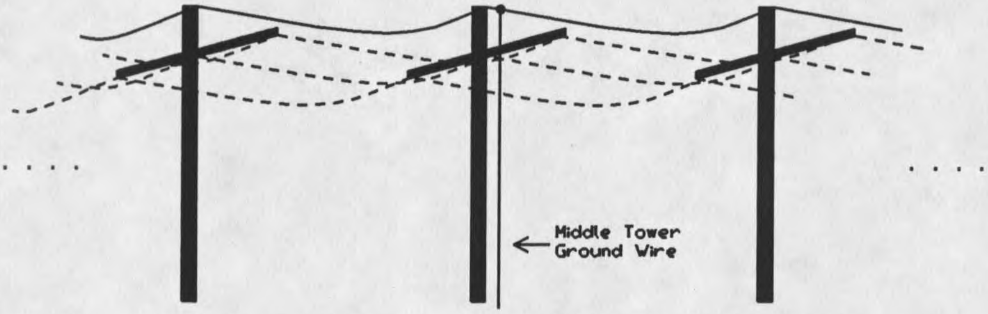


Figure 1. Fault Location System

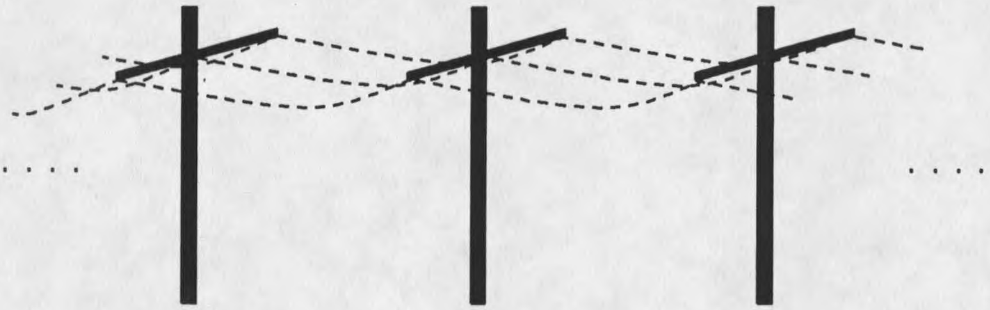
current. The Fault Detectors receive information on the fault currents at their particular tower from their sensors placed on the static wire and/or on the tower itself. Type I Fault Detectors make a decision whether the fault occurred at the tower or not based on the direction of currents in the static wire. If the fault is at the tower, the Fault Detector transmits a message frame containing the Tower Identification Code and the type of fault. If the fault is at another tower no message frame is transmitted by the Fault Detector. Conversely, Type II Fault Detectors always transmit a message frame when activated by fault current. The transmissions from adjacent towers are staggered in time according to Tower Identification Code to prevent simultaneously transmitted frames from interfering with one another. The message frames contain the Tower Identification Code and a value proportional to the RMS value of fault current down the tower.



Type I - Three Phase With Static Wire Grounded At Each Tower



Type II - Three Phase With Sectionalized Static Wire



Type III - Three Phase With No Static Wire

Figure 2. Power Transmission Line Configurations

Transmission Line Configurations

In this thesis, overhead power transmission lines are classified according to the arrangement of the static wire (Figure 2). In Type I line configuration the static wire is grounded at each tower by a tower ground wire. Type II line configuration is a sectionalized line in which the static wire is divided into segments (typically six miles long) that are insulted from one another. The middle of each of these segments is grounded by a tower ground wire. The segment is insulated from all other towers. Type III line configuration consists of no static wire. Type I Fault Detectors are installed on Type I transmission lines while Type II Fault Detectors are installed on Type II and Type III transmission lines.

Type I Line Configuration

Most overhead power transmission lines used by Montana Power Company are Type I configuration. Because of this, most of the work described in this thesis pertains to fault detection for Type I transmission lines.

Phase To Ground Fault Currents

Current flows away from the faulted tower through the static and tower ground wires during a phase to ground fault. The static and tower ground wires can be modeled as an impedance ladder network (Figure 3). The current splits according to the current divider rule. The current splits evenly if the impedances seen by the fault

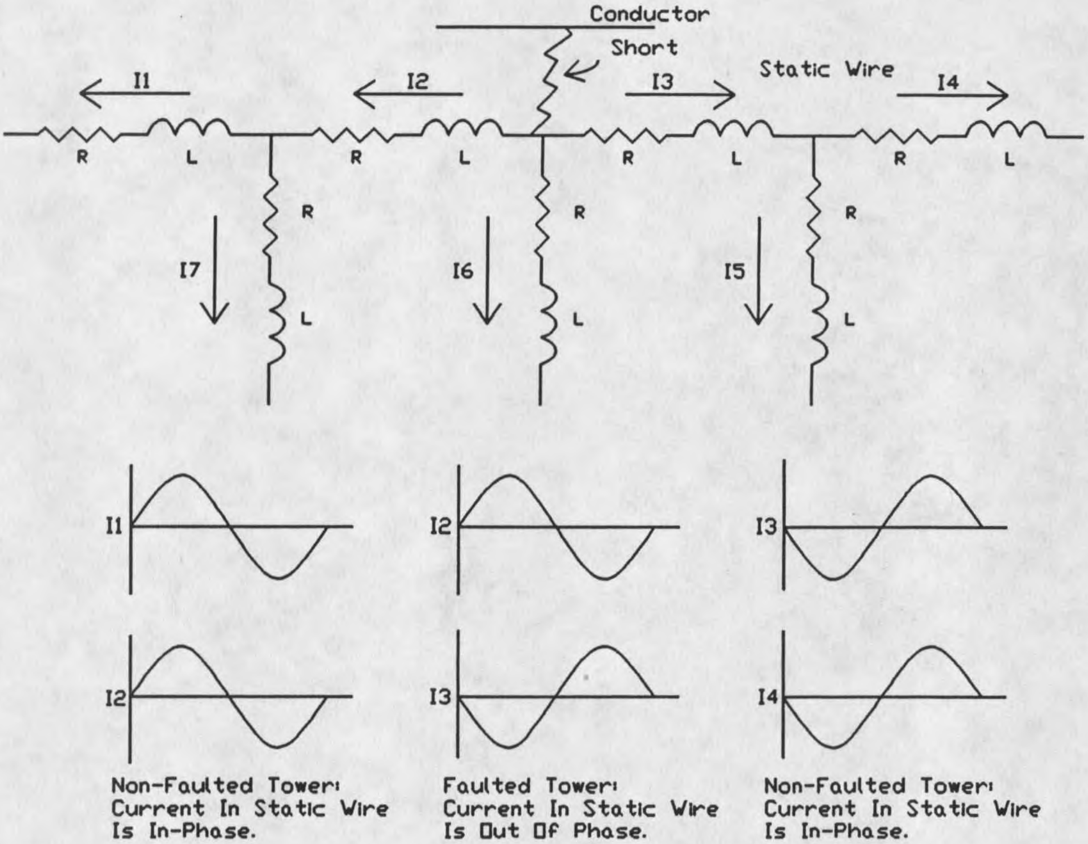
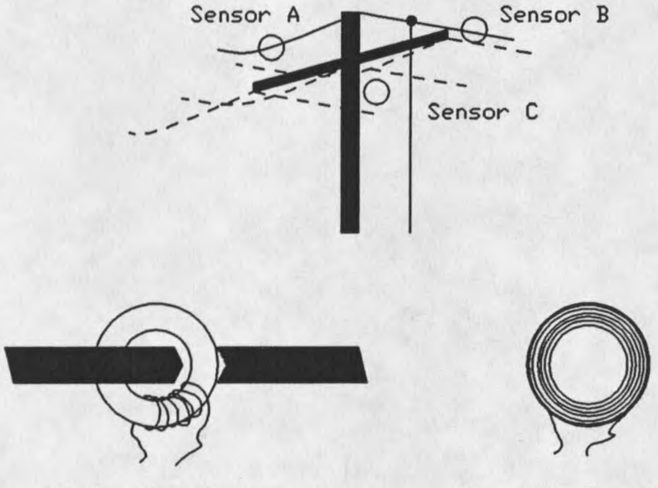


Figure 3. Type I Line Configuration Phase to Ground Fault Currents

current are equal on each side of the tower. In a realistic situation the impedances are not equal on each side of the tower. Differences in impedances are due to different ground resistances, poor connections, tower being at the end of the transmission line, etc. Unequal impedances cause more current to flow on one side of the tower than on the other side. If there is a large enough difference most of the current flows on one side of the tower and the current on the other side may not be distinguishable from noise present in the static wire. In either case the current in the static wire flows (1) in the same direction through the non-faulted towers and (2) in opposite direction at the faulted tower (Figure 3). Furthermore, the fault current in the static wire becomes less farther away from the faulted tower due to current flow to the ground at each grounded tower to which the static wire is connected.

Static Wire Current Sensors

Current sensors are placed around the static wire on each side of the tower to sense the fault current direction. The current sensor consists of a secondary winding wrapped around a ferromagnetic ring. The static wire runs through the center of this ring and acts as a primary winding (Figure 4). The current sensor design allows only the current in the static wire to develop a voltage on the secondary terminals. Flux produced by current outside of the ring will not develop a voltage on the secondary terminals of the sensor.



Static Wire Sensor
(Sensors A and B)

Perpendicular Flux Sensor
(Sensor C)

Figure 4. Type I Line Configuration Current Sensors and Their Placement

The total flux in the core of the ring is

$$\Phi_t = A\frac{\mu_o \mu_r I \sin\omega t}{2\pi r} \tag{1}$$

where A = cross-sectional area of the core, m^2
μ_o = permeability of free space, $4\pi \times 10^{-7}$ H/m
μ_r = relative permeability of the core
I = fault current in the static wire, A
ω = frequency of the current, rad/sec
r = average distance from the static wire to the core, m.

The voltage developed on the terminals of the secondary winding can be calculated by combining equation (1) with Faraday's Law,

$$V = -N\frac{d\Phi_t}{dt} \tag{2}$$

where N = number of turns on the secondary winding.

This result is shown as equation (3).

$$V = -N\frac{\omega A \mu_o \mu_r I \cos\omega t}{2\pi r} \tag{3}$$

The voltage induced across the secondary terminals is used to sense the direction of the fault current in the static wire (Figure 3).

The placement of the sensors on the static wire is important (Figure 4). A sensor is placed on the static wire on each side of the tower. In addition, the orientation of these two sensors must be the same, otherwise the information regarding fault current direction is lost.

Phase To Phase Fault Currents

Current flows between the phases through the short during a phase to phase fault (Figure 5). The current flow in the shorting arc is perpendicular to the current flow in the phase conductors. Thus the flux developed by the current in the arc is also perpendicular to the flux developed by the current in the phase conductors.

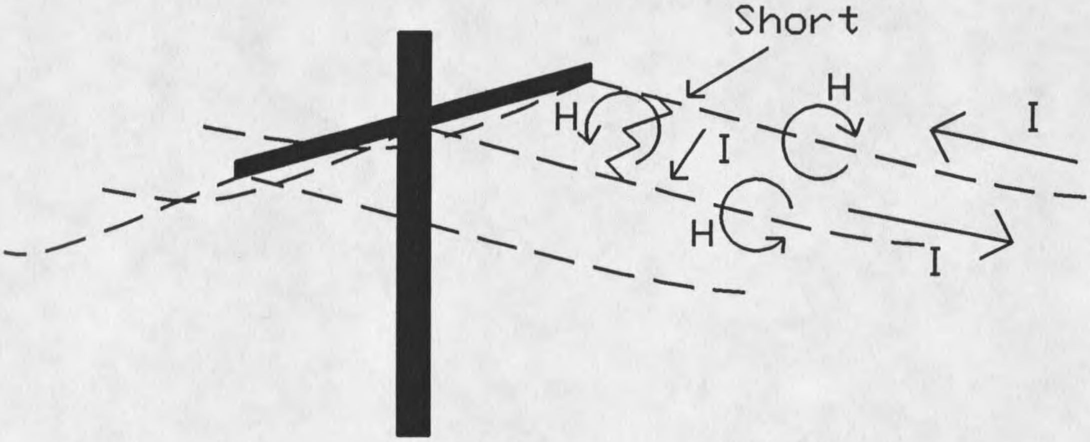


Figure 5. Type I Line Configuration Phase to Phase Fault Currents

Perpendicular Flux Sensor

An air core sensor is used to detect the presence of flux from the shorting arc during a phase to phase fault. The sensor is placed directly on the tower with the plane of the sensor perpendicular to the phase conductors. It has been shown that locating a sensor in this manner will only detect the flux produced by the shorting arc and not the flux produced by the current in the phase conductors during normal operation of the transmission line [6]. Figure 4 shows the design and location of the sensor. No significant fault current is present in the static wire during a phase to phase fault. The voltage developed on the terminals of the air core sensor is given by

$$V = -N\frac{\omega A \mu_o \mu_r I \cos\omega t}{2\pi r} \tag{4}$$

where A = area of the circle formed by the sensor windings
r = the average distance from the shorting arc to the sensor windings.

Type II Line Configuration

The Montana Power Company's 500 KV transmission line is a Type II line configuration since the static wire is insulated from the tower using a 12.5 KV insulator. The static wire consists of sections of approximately six miles long, grounded in the middle only at one tower, and insulated from the adjoining six mile sections (Figure 2).

Phase To Ground Fault Currents

During a phase to ground fault the current flows down the faulted tower into the ground (Figure 6). Additionally, a flash-over across the insulator between the faulted tower and the static wire may cause current flow in the static wire. This current may again flash-over from the static wire to adjacent towers. Eventually some current may flow down the grounded tower (i.e. center tower of the 6 mile segment). Ground impedance, insulator breakdown voltage and static wire impedance between towers will affect the amount of current in the static wire. In any case, the current down the tower where the fault occurs should be greater than at any other tower.

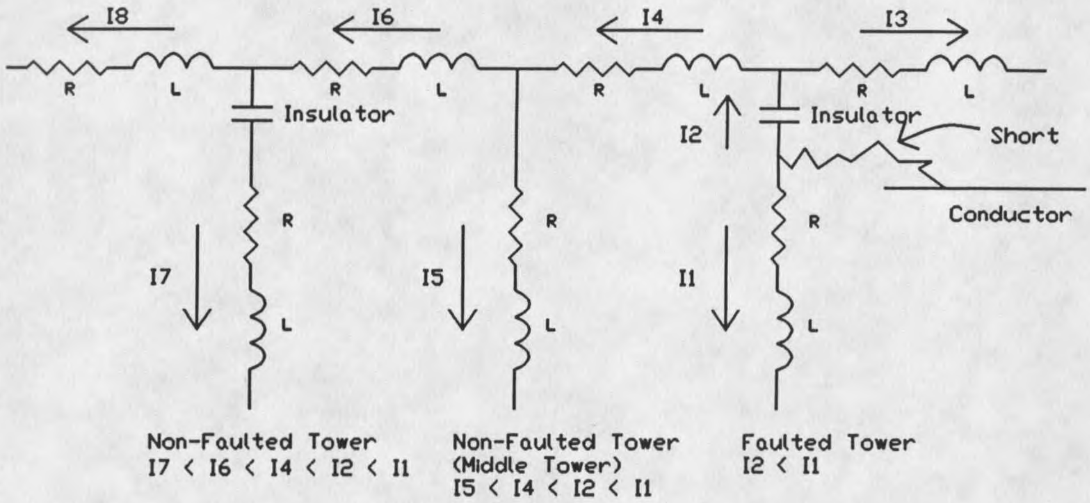


Figure 6. Type II Line Configuration Phase To Ground Fault Currents

<u>Tower Current Sensors</u>

Current sensors are placed around one leg of the tower structure to sense the magnitude of fault current down the tower. The four current sensors are separate windings wrapped around an air core ring. Each sensor has a different number of turns so that the amplitude of fault current can be determined accurately. Only the current flow in the tower leg will create a voltage on the winding terminals (effect of outside flux is minimized). Figure 7 shows the design and location of these sensors.

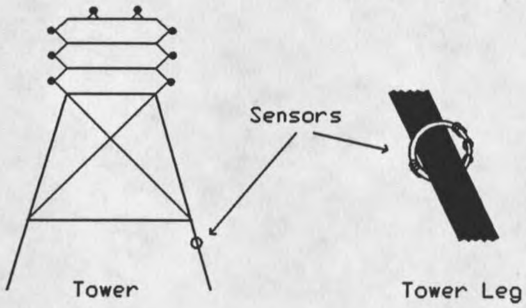


Figure 7. Type II Line Configuration Current Sensors and Their Placement

CHAPTER 3

FAULT DETECTORS

A Fault Detector is mounted on each tower of the overhead power transmission line. All Fault Detectors on a single line must be of the same type. (Type I Fault Detectors are used on Type I line configurations while Type II Fault Detectors are used on Type II and Type III line configurations.) Although, Type I and Type II Fault Detectors use different sensors both systems use the same hardware for the Fault Detector unit itself. However, the software interrupt service routine that is executed by the microcontroller for determination of fault location is different for the two types.

Instrumentation

The Fault Detector as shown in Figure 8 has the following subsystems:

1. Power Source
2. Sensors
3. Amplifier and Comparator Circuit
4. Software Based Logic (Microcontroller)
5. Analog to Digital Convertor
6. Tower Identification Code
7. Communications

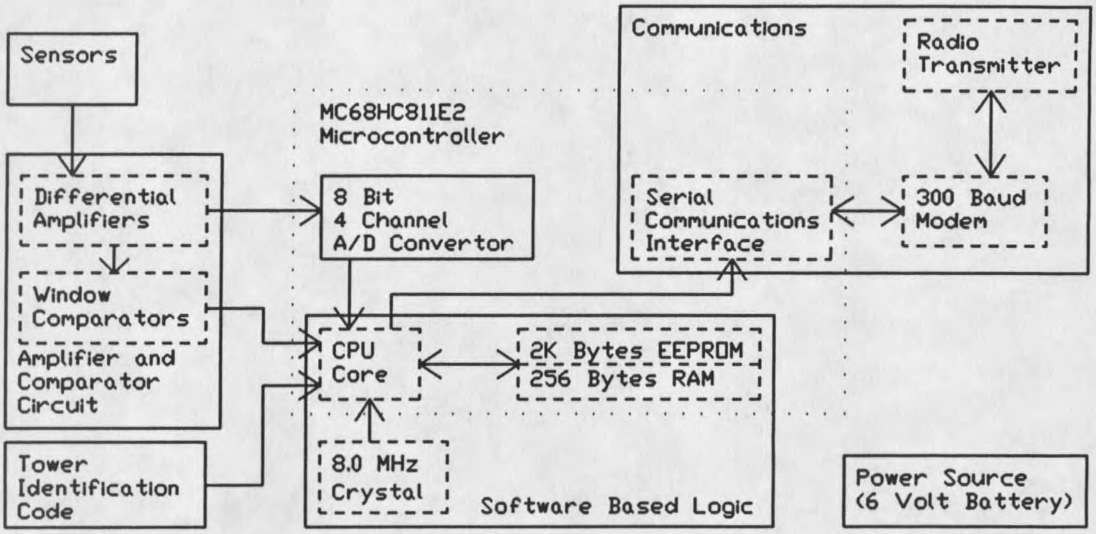


Figure 8. Fault Detector Subsystems Block Diagram

Power Source

The Fault Detectors are self contained and require only solar power. This is required since it would not be feasible to bring power to each unit along a transmission line. The Fault Detector is placed in a low power mode while waiting for a fault to occur. In this mode only the Amplifier and Comparator Circuit and the Microcontroller (in a low power wait state) are using power. The Analog to Digital Convertor, Tower Identification Code and Communications subsystems are turned on only when a fault has occurred. A 6 volt, 1.2 amp hour rechargeable acid gel battery is used to power the unit. In wait mode the current drawn by the unit is 4.3 milliamps. The battery can power the unit for over 11 days (1.2 amp hour / 4.3 milliamps = 279 hours). The battery is charged by a solar panel attached to it.

Table 1 shows the current delivered by the 6 volt rechargeable battery to the Fault Detector in different modes of operation.

Table 1. Current Drawn By Fault Detector

Mode	Current (milliamps)	Time
Low Power (Wait)	4.3	usual mode
Fault Processing: switches off switches on	 12.0 17.7	 2 minutes 1 second
Transmitting	18.8	twice for 1.5 to 4 seconds

Sensors

For Type I Fault Detectors, Sensor A and Sensor B sense the fault current direction in the static wire during a phase to ground fault. Sensor C is mounted on the tower and senses the flux developed by a short or flash-over during a phase to phase fault. The output of these sensors are the voltage inputs to amplifiers A, B and C respectively (amplifier D is not used).

For Type II Fault Detectors, all four sensors sense the magnitude of fault current flowing down the tower. The sensors are connected to amplifiers A, B, C and D. The sensor with the lowest number of turns is connected to amplifier A, the sensor with the next lowest number of turns is connected to amplifier B and so forth.

In Type I Fault Detectors the wires connecting the sensors to the Fault Detectors may be long (e.g. up to 60 feet in length). A voltage may be developed on these wires since the sensor end will be near high electro-static field and the Fault

Detector end will be near ground potential. The wires are encased in a grounded metallic shield to reduce this noise voltage.

Amplifier And Comparator Circuit

A differential amplifier is used to increase the voltage signal from the sensor since this amplifier configuration has low common mode gain. Due to the Fault Detector power being supplied by a battery the operational amplifier itself must have low power consumption and run off a single voltage supply (i.e. Vcc or +5 volts). A pseudo-ground at ½Vcc or 2.5 volts is used. Large resistor values are used to minimize power consumption and to increase input resistance.

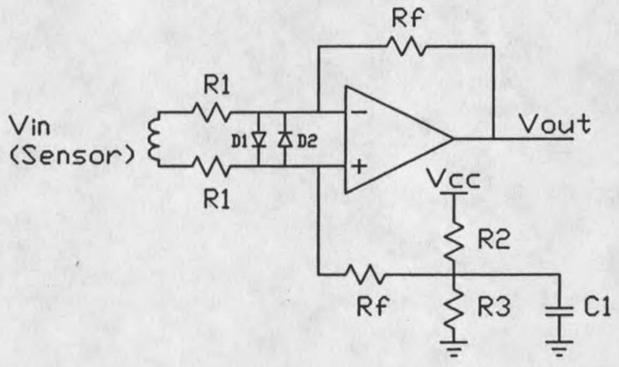


Figure 9. Differential Amplifier

The outputs of the amplifiers are connected to the Analog to Digital Convertor (contained within the microcontroller). Additionally, the outputs of amplifiers B and C are connected to window comparators (Figure 10). The output signal from the comparator circuit is connected to the external interrupt pin of the microcontroller. Until a fault occurs the voltage on Sensors B and C will be minimal and therefore the

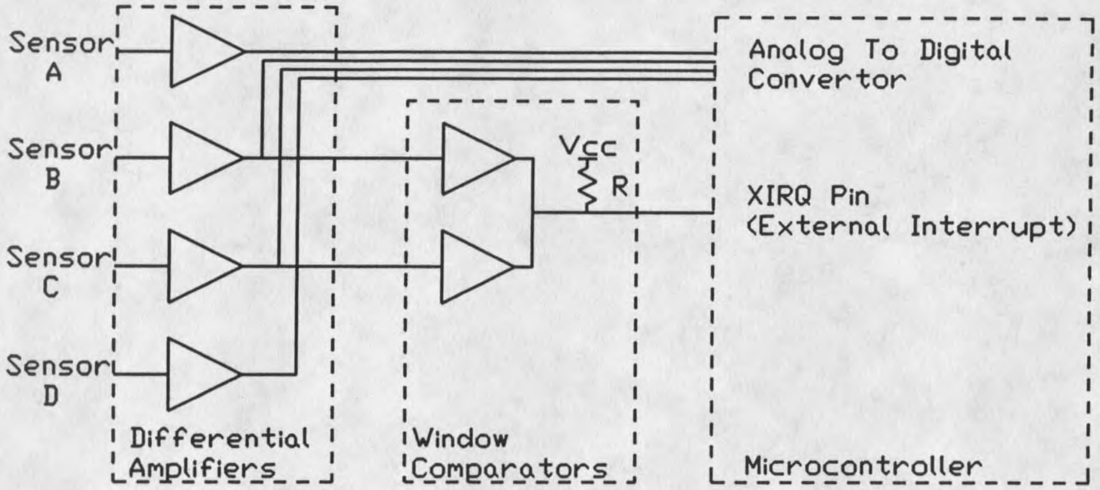


Figure 10. Amplifier and Window Comparator Circuits

output of the comparator circuit will be a logic high (i.e. Vcc). When a fault occurs the amplified signal of Sensor B or C will swing below ⅓Vcc or above ⅔Vcc. When this happens the output of the comparator circuit will be a logic low (i.e. 0 volts). The interrupt service routine software is executed once the external interrupt pin receives this logic low signal.

Microcontroller

A Motorola MC68HC811E2 microcontroller is used. The software program is described in Software Based Fault Detection Logic below. The Analog to Digital (A/D) Convertor and Serial Communications Interface (SCI) subsystems are contained within the microcontroller. The code executed by the microcontroller is stored in 2K bytes of internal EEPROM. The digital data from the A/D Convertor are stored in

192 bytes of the 256 byte RAM while the remaining 64 bytes are used for the stack, the message frame, and other variables needed by the microcontroller. The microcontroller uses a 2 MHz clock frequency.

Analog To Digital Convertor

The four channel A/D Convertor digitizes analog voltage signals provided by the amplifier circuits. An analog voltage level is converted into an eight bit digital data byte in 16 microseconds (four channels in 4 * 16 microseconds or 64 microseconds). The period of a 60 Hz wave is 16.67 msec. For Type I Fault Detectors, two cycles of the signal waves are digitized at 1920 samples per second (i.e. 64 samples for each sensor: A, B and C). For Type II Fault Detectors, two cycles of the signal waves are digitized at 1440 samples per second (i.e. 48 samples for each sensor: A, B, C and D). Because of the pseudo-ground used in the amplifier circuit a digital 80H is considered "ground" or no induced voltage, FFH is +2.5 volts and 00H is -2.5 volts. The digital data are stored in RAM and later analyzed by the software.

Tower Identification Code

The Tower Identification Code is selected by 12 binary switches. The switches are set to a unique code (one of 2^{12} or 4096) by a lineman when the Fault Detector is installed on the tower. To reduce the power used by the circuit the switches are tied to Vcc and electrically disconnected from ground using a transistor switch. Just before the binary switches are read the transistor switch is turned on to complete the power supply circuit to the binary switches. The Tower Identification Code is then read and stored in RAM. The transistor switch is then turned off to conserve power.

Communications

The Fault Detectors are non-interrogative, that is, message frames are transmitted but no message or control frames are received. The communications are controlled by the Serial Communications Interface (SCI) within the microcontroller. Standard non-return to zero (NRZ) format (i.e. one start bit, eight data bits, and a stop bit) at 300 BAUD is used. A National Semiconductor MM74HC943 Modem in Originate Mode is used to frequency shift key (FSK) the NRZ output of the microcontroller. The dual tone frequency allocation is given in Table 2. An FM transceiver is used to transmit the FSK signals at 49.8 MHz. The entire communications subsystem (i.e. SCI, Modem and Transceiver) is turned on only when a message frame is transmitted, otherwise the subsystem is turned off to save power.

Table 2. Frequency allocation of MM74HC943 Modem

Data	Originate Mode		Answer Mode	
	Transmit	Receive	Transmit	Receive
Low (Space)	1070 Hz	2025 Hz	2025 Hz	1070 Hz
High (Mark)	1270 Hz	2225 Hz	2225 Hz	1270 Hz

Error correction encoding is used to improve data reliability. A systematic (7,4) Hamming code is used; the low four bits of the codeword are the same as the four bits of the uncoded data nibble (Appendix A, Table 4). The data nibbles are encoded using a look-up table that is implemented in software. A single bit error per byte can be corrected by this code.

Each transmission of data bytes (i.e. message frame) follows a specific format defined for the Fault Location System. The first byte identifies the transmission as a message frame of the Fault Location System. The second byte identifies the type of message frame (e.g. Type I Fault Detector message frame, etc.). Then follows all the bytes of data for the message frame. A list of all the message frame types is shown in Figure 18 in Appendix A.

Software Based Fault Detection Logic

The software for the Fault Detector is stored in the 2K bytes of EEPROM within the microcontroller. The main program for both Type I and Type II Fault Detectors is the same (Figure 11). On the other hand, the interrupt service routines for the two detectors are different (Figure 12 and Figure 13).

Upon powering the system (i.e. Power On Reset) and after initialization, the microcontroller is placed in a low power wait mode. The microcontroller is awakened from this mode by an interrupt signal from the window comparator circuit when a fault occurs. Depending on the type of Fault Detector, either the Type I Fault Detector interrupt service routine or the Type II Fault Detector interrupt service routine is executed. While servicing the interrupt the microcontroller ignores any additional interrupt requests preventing additional interrupts from the same fault.

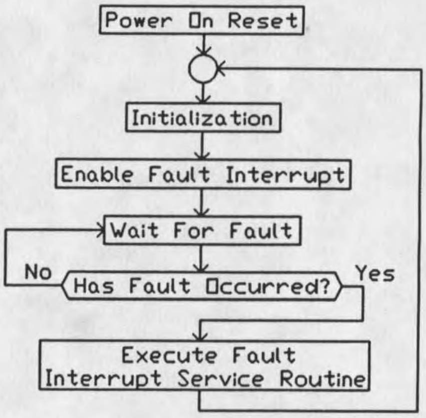


Figure 11. Fault Detector Main Software Routine Flow-Chart

After servicing the interrupt the microcontroller is again placed in the low power mode and waits for another fault to occur.

Type I Fault Detector

The interrupt service routine for the Type I Fault Detector is shown in Figure 12. First, the sensors are read and the fault type determined. If the Fault Detector determines that the fault is at another tower it waits before returning to the main program. This delay prevents additional interrupts from the same fault. On the other hand, if the Fault Detector determines that the fault is at the tower the Tower Identification Code switches are read and a message frame is built and transmitted. After a sixty second delay the message frame is retransmitted in case the first message frame was not received correctly. The interrupt service routine then returns to the main program.

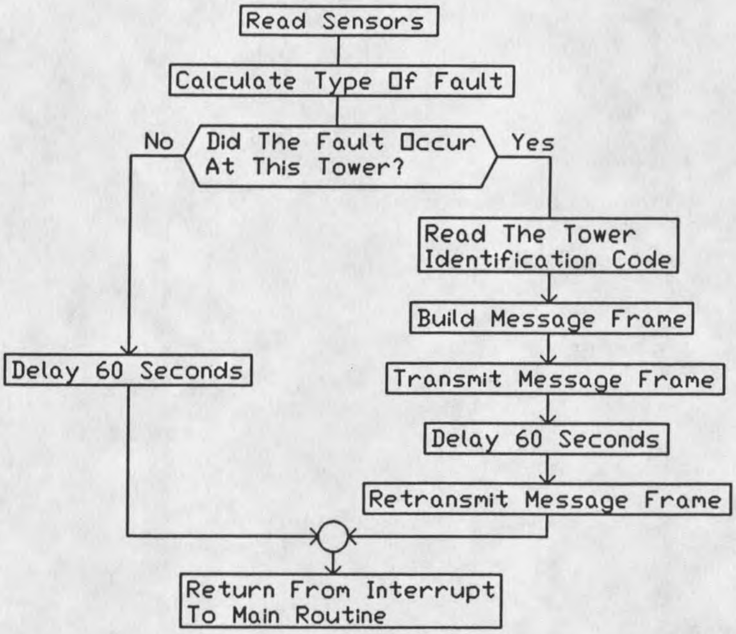


Figure 12. Type I Fault Detector Interrupt Service Routine Flow-Chart

The software subroutines are described below:

READ SENSORS - The analog signals from the three sensors (i.e. A, B and C) are digitized by the Analog to Digital Convertor. Two cycles of the 60 Hz waveforms are obtained (i.e. 64 samples for each sensor at 1920 samples per second). The digitized values are stored in RAM.

CALCULATE TYPE OF FAULT - Faults are classified into one of the following categories and also summarized in Table 3:

Phase to Ground - Current in the static wire flows in opposite direction on each side of the tower; The voltages induced in sensors A and B are **out of**

phase or present only in sensor B; . Voltage may be induced in sensor C due to current flowing in the tower ground wire but is ignored.

Other Tower - Current in the static wire flows in the same direction on each side of the tower; The voltages induced in sensors A and B are **in phase.** Voltage may be induced in sensor C due to current flowing in the tower ground wire but is ignored.

Phase to Phase - No current flow in the static wire; No voltage induced in sensors A and B. Voltage induced in sensor C due to flux from short current between conductors.

Table 3. Determination Of Fault Type Logic

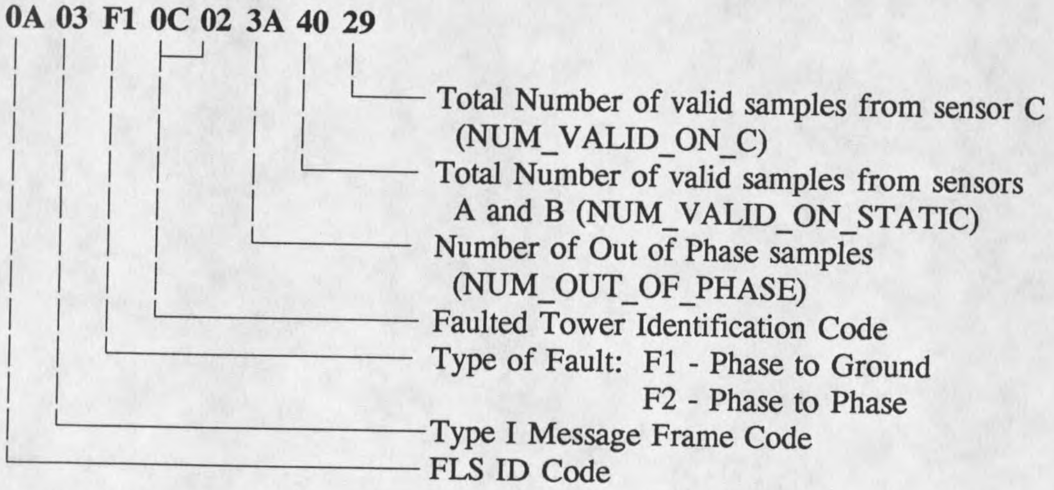
Fault Type	Voltage Induced In Sensors A and B		Voltage Induced In Sensor C
	Present	Out Of Phase	
Phase to Ground	Yes	Yes	*
Other Tower	Yes	No	*
Phase to Phase	No	*	Yes

* Don't care for fault determination

The software uses three internal variables: NUM_VALID_ON_STATIC, NUM_OUT_OF_PHASE, and NUM_VALID_ON_C to determine the fault type. NUM_VALID_ON_STATIC is the total number of sets of samples that either one or both of the samples from sensor A and sensor B are outside a region centered about the "ground" value of 80H. These samples can be either in or out of phase (e.g. 45H & 50H, in phase samples; 45H & 7AH, 45H & B8H, out of phase samples). If NUM_VALID_ON_STATIC is greater than a preassigned minimum value then current is flowing in the static wire. NUM_OUT_OF PHASE is the total number of sets of samples included in NUM_VALID_ON_STATIC in which the sample from sensor A and the sample from sensor B are on opposite sides of the ground region (e.g. 45H & A7H). These samples are considered to be out of phase. If NUM_OUT_OF_PHASE is greater than 70 percent of NUM_VALID_ON_STATIC then the current flow in the static wire is away from the tower. NUM_VALID_ON_C is the total number of samples from sensor C that are outside the ground region. If NUM_VALID_ON_C is greater than a minimum value then current flow perpendicular to the line conductors has occurred.

READ TOWER IDENTIFICATION CODE - Power is turned on to the 12 binary switches. The switches are read and the corresponding binary code is stored in RAM. The power to the switches is then turned off.

BUILD MESSAGE FRAME - The message frame is built and stored in RAM. A typical Type I message frame is as follows:



TRANSMIT MESSAGE FRAME - All the communications subsystems (i.e. SCI, Modem, and Transceiver) are turned on. Each byte of the message frame is encoded and transmitted. The communications subsystems are then turned off.

DELAY SIXTY SECONDS - The microcontroller delays execution for sixty seconds. This delay prevents additional interrupts from the same fault.

RETRANSMIT MESSAGE FRAME - Transmit the message frame again in case the first message frame was not received correctly.

Type II Fault Detector

The interrupt service routine for the Type II Fault Detector is shown in Figure 13. First, the sensors are read and a value proportional to the RMS current flowing down the tower is calculated for all four sensors. Next, the Tower Identification Code switches are read. Processing is then delayed an amount based on the Tower Identification Code. After the delay, the message frame is built and transmitted. Then after a sixty second delay the message frame is retransmitted in case the first message frame was not received correctly. The interrupt service routine then returns to the main program.

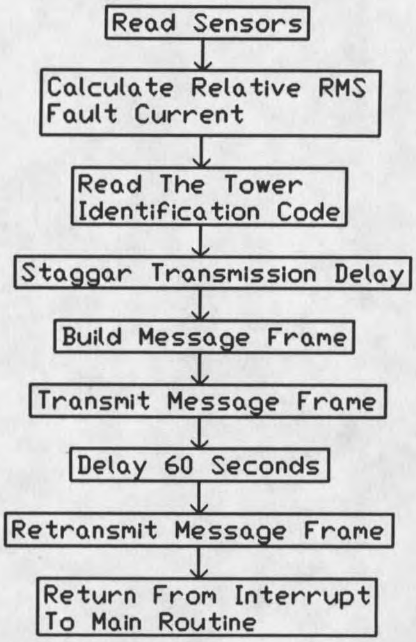


Figure 13. Type II Fault Detector Interrupt Service Routine Flow-Chart

The software subroutines are described below:

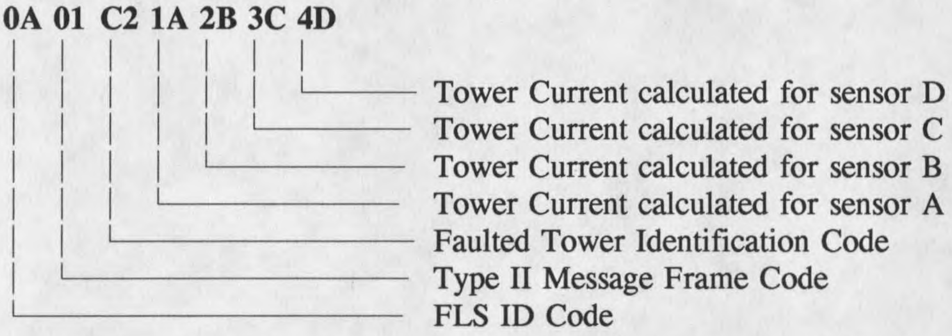
READ SENSORS - The analog signals from the four sensors are digitized by the Analog to Digital Convertor. Two cycles of the 60 Hz waveforms are obtained (i.e. 48 samples for each sensor at 1440 samples per second). The digitized values are stored in RAM.

CALCULATE RELATIVE RMS FAULT CURRENT - The stored data samples from all four sensors are analyzed. Values proportional to the RMS fault current are calculated. These values will be transmitted in the message frame. The operator at the power company's headquarters makes a decision on the fault location based on these values.

READ TOWER IDENTIFICATION CODE - Power is turned on to the 12 binary switches. The switches are read and the corresponding binary code is stored in RAM. The power to the switches is then turned off.

TOWER TRANSMISSION DELAY - The Fault Detector delays transmission by a specified amount of time according to its Tower Identification Code. This prevents simultaneous transmissions from adjacent towers.

BUILD MESSAGE FRAME - The message frame is built and stored in RAM. A typical Type II message frame is as follows:



TRANSMIT MESSAGE FRAME - All the communications subsystems (i.e. SCI, Modem, and Transceiver) are turned on. Each byte of the message frame is encoded and transmitted. The communications subsystems are then turned off.

DELAY SIXTY SECONDS - The microcontroller delays execution for sixty seconds. This delay prevents additional interrupts from the same fault.

RETRANSMIT MESSAGE FRAME - Transmit the message frame again in case the first message frame was not received correctly.

CHAPTER 4

REPEATER

The Repeater receives and retransmits all Fault Location System message frames. Extraneous transmissions not having the Fault Location System start byte are ignored.

The Repeater has the following subsystems:

1. Microcontroller (Software Based Control)
2. Communications
    a. Reception
    b. Error Correction
    c. Transmission
3. Repeater System Check
4. Optional Liquid Crystal Display (Monitor)

Software And Communications

The Repeater uses the same microcontroller as the Fault Detector (i.e. Motorola MC68HC811E2). The set up is similar to the Fault Detector but the Repeater software does not have any interrupt service routines. Instead, the Repeater continuously receives and transmits message frames. The flow-chart for the Repeater software is shown in Figure 14. Error correction is performed in software on the received frames before being retransmitted (Appendix A - Error Correcting Code).

The Repeater receives transmissions at all times except while transmitting or during a one minute delay after transmitting. The purpose of delaying reception is to

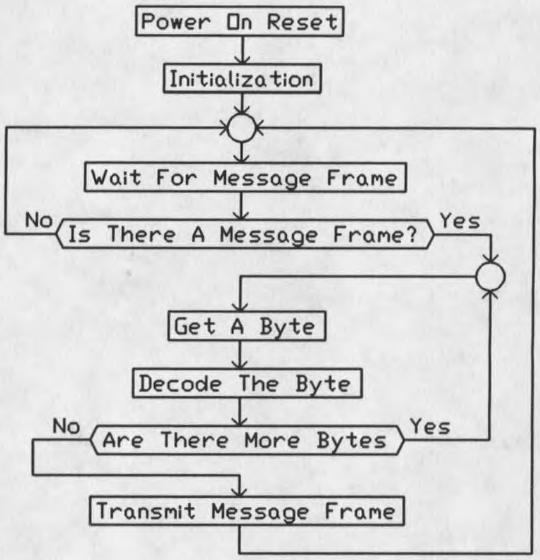


Figure 14. Repeater Main Software Routine Flow-Chart

avoid feedback. Feedback will occur without the delay because the originating Repeater will receive the transmitted frame of the next Repeater. This newly received frame will be sent again by the originating Repeater and an endless cycle of transmissions will occur. The Repeater receives message frames in Answer Mode and transmits in Originate Mode (Table 2).

The software subroutines are described below:

POWER ON RESET - Starting location of software when power is initially given to the microcontroller.

INITIALIZATION - Set up variables and other system parameters.

WAIT FOR MESSAGE FRAME - Monitor receiver until a start byte for a message frame of the Fault Location System is received.

GET A BYTE - Relocate the received byte from the receiver into the microcontroller.

DECODE THE BYTE - Decode the received byte. Calculate the syndrome. Correct single bit errors.

ARE THERE MORE BYTES - Check the receiver for any more bytes in the message frame.

TRANSMIT MESSAGE FRAME - Rebuild the received message frame. Each byte of the message frame is encoded and transmitted.

Repeater System Check

The station at the power company's headquarters controls the 24 Hour Repeater System Check. The check begins with a search for the last Repeater in the system along the transmission line. The Repeater System is considered fully functional if an acknowledgement from the last Repeater is received. If the check frame is not acknowledged within the specified time limit the station sends out a search frame for the next closest Repeater. If an acknowledgement is again not received then the station searches for the next closest Repeater. The station continues to search in this fashion for the farthest Repeater acknowledging its check frame. The first Repeater beyond the acknowledging Repeater is considered inoperable. A lineman is then sent to the Repeater to correct the problem.

Optional Liquid Crystal Display

A Repeater can be equipped with a Liquid Crystal Display (LCD) for monitoring and testing purposes. Received message frames are stored in RAM and also displayed. Up to 8 message frames can be stored. They can be recalled and paged through by the operator. The Monitor in the control room can be a Repeater with this option.

CHAPTER 5

EXPERIMENTS AND RESULTS

A scaled model power transmission line in Ryon Laboratory and an experimental low tension power transmission line next to the Huffman Building on the Montana State University (MSU) campus have been used to simulate faults to test the Fault Location System. Additionally, the equipment used and the results obtained from phase to ground and phase to phase fault tests conducted on 100 KV (Two Dot) and 115 KV (Conrad Auto) transmission lines are given. The proposed 500 KV line fault test detection scheme and sensor configuration are also outlined.

Fault Tests At Montana State University

A scaled model three phase transmission line (Type I configuration) in Ryon Laboratory has been used to simulate faults. The transmission line consists of three phase lines at 120 volts plus a static wire grounded at each tower. The line is five spans in length. A load of 50 amps is connected at the end of the line on each phase. The power is supplied through a 150 amp breaker. A low tension three phase transmission line in the field next to the Huffman building on the MSU campus has also been used to simulate faults. It is larger in scale than the Ryon Laboratory line. It also is a Type I configuration transmission line at 120 volts with five spans but no load is connected to the line.

Faults are achieved by placing a shorting wire between one phase and the static wire or between two phases. The shorting wire is insulated from the operator by a long wooden pole. Results from several tests are summarized in Appendix B - Statistical Results.

Fault Test At Conrad Auto

The fault test at Conrad Auto was conducted on May 30, 1991. One phase to ground fault and one phase to phase fault were conducted on the 115 KV line between breaker number 100-104 Cut Bank Glacier CO-OP substation and breaker number 69-45 Conrad Auto substation. The fault was achieved by closing breaker number 100-104 with a dead short at tower number 35-14 located near breaker number 69-45. Fault test data are shown in Appendix C - Conrad Auto.

Equipment Placement For Fault Test

The test equipment was placed as shown in Figure 15. Due to the location of the faulted tower only two instrumentation sites were used. Specifically, data from the faulted tower, number 35-14, and the adjacent tower, number 35-15, toward breaker number 100-104 were obtained.

Fault Test Equipment

Recorder. Two Digital Transient Fault Recorders, designated as FLS-02DR01, were used to obtain fault current data at each tower. This version of Recorder has the

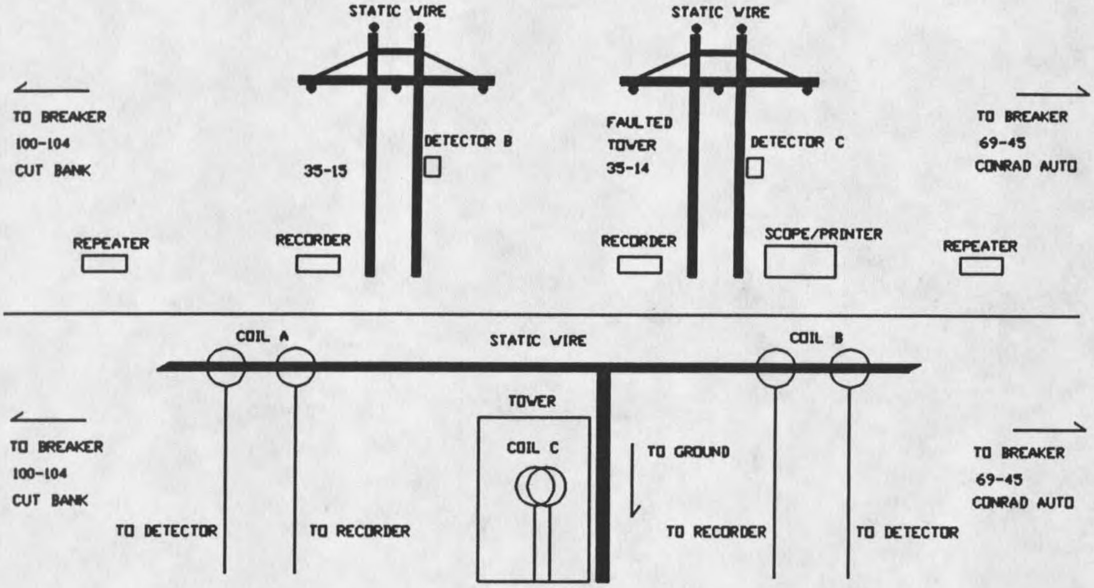


Figure 15. Fault Test At Conrad Auto Equipment Configuration

following characteristics:

1. Non-inverting amplifier configuration
2. Records 64 samples at 500 usec. interval between samples, i.e. 2 cycles of data
3. Capable of sampling four channels
4. Computer interface for data upload
5. On-board display of digital data

The Recorders were connected to an independent set of sensors, separate from the Fault Detector sensors. The Recorders stored two cycles of digital data (32 msec.) which were subsequently uploaded to a computer disk. The data were later graphed as shown in Appendix C - Conrad Auto.

Scope. A digital storage oscilloscope was connected to the outputs of the amplifiers on the Recorder placed at the faulted tower. A portable generator

(120 Volts, 60 Hz) was used to power the computer, oscilloscope, and printer. This power source was not stable. As a result the data from the scope for sensors A and B could not be obtained.

Fault Detector. Two Type I Fault Detectors, designated as FLS-02FD01, were used to determine the location of the fault. This version of Type I Fault Detectors use the detection scheme discussed in Software Based Fault Detection Logic section. These Fault Detectors also employed a non-inverting amplifier configuration.

Repeater/Monitor. Two Repeater/Monitors, designated as FLS-02RM01, were used to receive and display the message frames transmitted from the Fault Detectors. Error correction and formatting of the received frame were not performed by the units at this time.

Fault Test Results

PHASE TO GROUND FAULT (NUMBER 5-30A):

Received Message Frame	**0C02F13A4029**
Faulted Tower Identification Code	0C02
Type of Fault	F1 (Phase to Ground)
Number of Valid Samples on Sensors A and B	64 (40 Hexadecimal)
Number of Out of Phase Samples	90.6% (58/64)
Number of Valid Samples on Sensor C	41 out of 64 samples

The out of phase current in the static wire at the faulted tower is shown by the high number of samples that are out of phase (90.6%) and the high number of valid samples (64). The number of valid samples on sensor C is irrelevant for a phase to ground fault. The Fault Detector at tower 0C02 correctly transmitted a message frame indicating a phase to ground fault (F1) at the tower. The Fault Detector at the adjacent tower did not transmit since the fault was not at that tower.

PHASE TO PHASE FAULT (NUMBER 5-30B)

Received Message Frame	**0C02F2000040**
Faulted Tower Identification Code	0C02
Type of Fault	F2 (Phase to Ground)
Number of Valid Samples on Sensors A and B	0
Number of Out of Phase Samples	0% (0/0)

No current in the static wire is shown by the low number of valid samples on Sensors A and B (0). The high number of valid samples on sensor C shows that current is flowing between phases. The Fault Detector at tower 0C02 correctly transmitted a message frame indicating a phase to phase fault (F2) at the tower. The Fault Detector at the other tower did not transmit since the fault was not at that tower.

Fault Test At Two Dot

The fault test at Two Dot was conducted on July 25, 1991. Two phase to ground faults and one phase to phase fault were conducted on the 100 KV line between breaker number 100-160 at the Two Dot substation and the Groveland air break. The fault was achieved by closing breaker number 100-160 with a dead short at a tower located approximately three miles east of the air break. Fault test data are shown in Appendix C - Two Dot.

Equipment Placement For Fault Test

The test equipment was placed as shown in Figure 16. Three instrumentation sites were used to collect data and locate the fault.

Fault Test Equipment

Recorder. Three Digital Transient Fault Recorders, designated as FLS-02DR02, were used to obtain data at each tower. This version of Recorder has the following characteristics:

1. Non-inverting amplifier configuration
2. User specified:
    a. Fault Number
    b. Sample Rate
    c. Number of Samples
3. Default setting records 534 samples at 250 usec. interval between samples, i.e. 8 cycles of data
4. Capable of sampling four channels
5. Computer interface for data upload
6. On-board display of digital data

The default settings were used to obtain data which were subsequently uploaded to a computer disk.

Scope. A digital storage scope was connected to the outputs of the amplifiers on the recorder placed at the faulted tower. A 12 Volt DC to 120 Volt AC invertor was used to power the computer, oscilloscope and printer.

Fault Detector. Three Type I Fault Detectors, designated as FLS-02FD01, were used to determine the location of the fault. The hardware and software detection scheme is the same as for the previous fault test at Conrad Auto. However, the

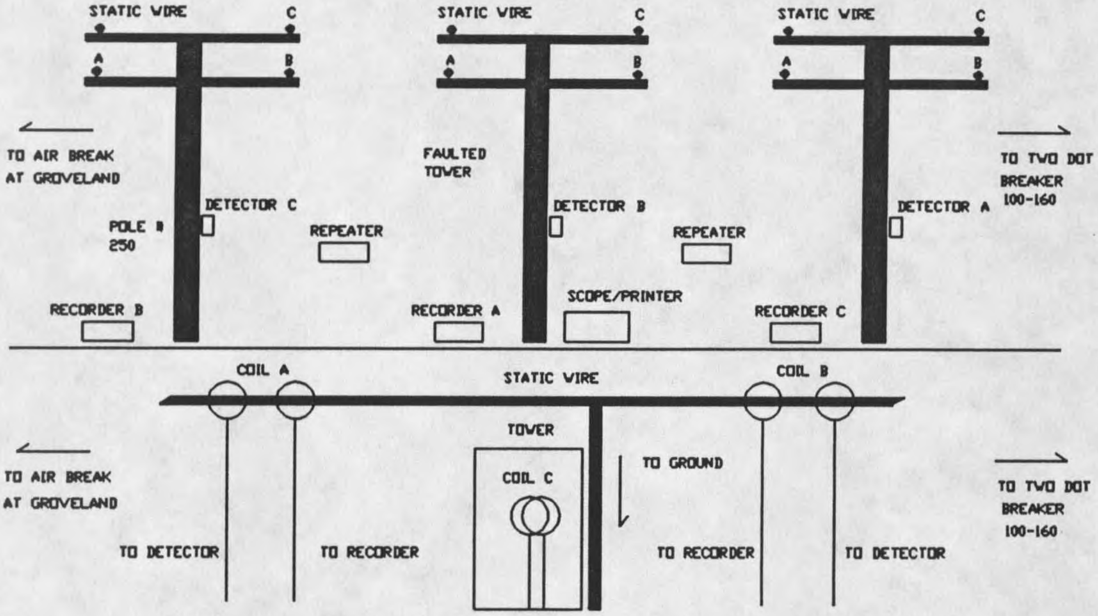


Figure 16. Fault Test At Two Dot Equipment Configuration

software for the detectors used at Two Dot contained error correction encoding for the transmitted message frames. Additionally, the transmitted message frames contain bytes used by the Repeater/Monitor for frame formatting.

Repeater/Monitor. Two Repeater/Monitors, designated as FLS-02RM02, were used to receive and display the message frame transmitted by the detectors. Error correction and formatting of the received frame were performed by the units. The Repeater/Monitors are capable of storing and recalling up to eight message frames.

The Repeater/Monitor displays the received message frame in the following format:

LGnd ╪B4 Σ1Eϕ1E Σ40

Total Number of Valid Samples on Sensor C
Total Number of Valid Samples on Sensors A and B
Number of Out of Phase Valid Samples
Faulted Tower Identification Number
Type of Fault

Note: All numbers are in hex.

Fault Test Results

FIRST PHASE TO GROUND FAULT:

Received Message Frame	**Lgnd ╪AC Σ23ϕ23 Σ0**
Faulted Tower Identification Code	AC
Type of Fault	Lgnd (Phase to Ground)
Number of Valid Samples on Sensors A and B	35 (23 Hexadecimal)
Number of Out of Phase Samples	100% (35/35)
Number of Valid Samples on Sensor C	0 out of 64 samples

Although the data received in the message frame seems reasonable the faulted Tower Identification Code is incorrect since no fault detection unit has code AC. The most likely reason for this is that two or more of the detection units calculated a fault and then transmitted message frames simultaneously. This occurred because the non-inverting amplifier configuration amplified the common mode signal. Subsequently, the phase relationship of the signal was lost.

SECOND PHASE TO GROUND FAULT:

Received Message Frame	**Lgnd ╪B4 Σ35ϕ3A Σ24**
Faulted Tower Identification Code	B4
Type of Fault	Lgnd (Phase to Ground)
Number of Valid Samples on Sensors A and B	58 (3A Hexadecimal)
Number of Out of Phase Samples	91.4% (53/58)
Number of Valid Samples on Sensor C	36 out of 64 samples

The out of phase current in the static wire at the faulted tower is shown by the high number of samples that are out of phase (91.4%) and the high number of valid samples (58). The number of valid samples on sensor C is irrelevant for a phase to ground fault. The Fault Detector at tower B4 correctly transmitted a message frame indicating a phase to ground fault (F1) at the tower. The Fault Detector at the other tower did not transmit since the fault was not at that tower.

PHASE TO PHASE FAULT:

Received Message Frame	No Frame Received

No message frame was transmitted from Fault Detectors for the phase to phase fault. The Fault Detectors at the non-faulted towers functioned correctly since they did not transmit a message frame. The Fault Detector at the faulted tower determined that the fault was at another tower and did not transmit a message frame. It was concluded that this malfunction was caused by transient noise which occurred during the first half cycle. It was also noted that significant common mode gain of the amplifiers for sensors A and B was present.

500 KV Line Fault Test Proposal

The detection scheme for the 500 KV fault test will consist of four sensor placed around one leg of the tower. Faults will be achieved similarly to the previous faults at Conrad Auto and Two Dot.

Fault Test Equipment Placement

The test equipment will be placed as shown in Figure 17. Five instrument sites will be used to collect data. Three of the five sites will be equipped with Type II Fault Detector units to locate the fault.

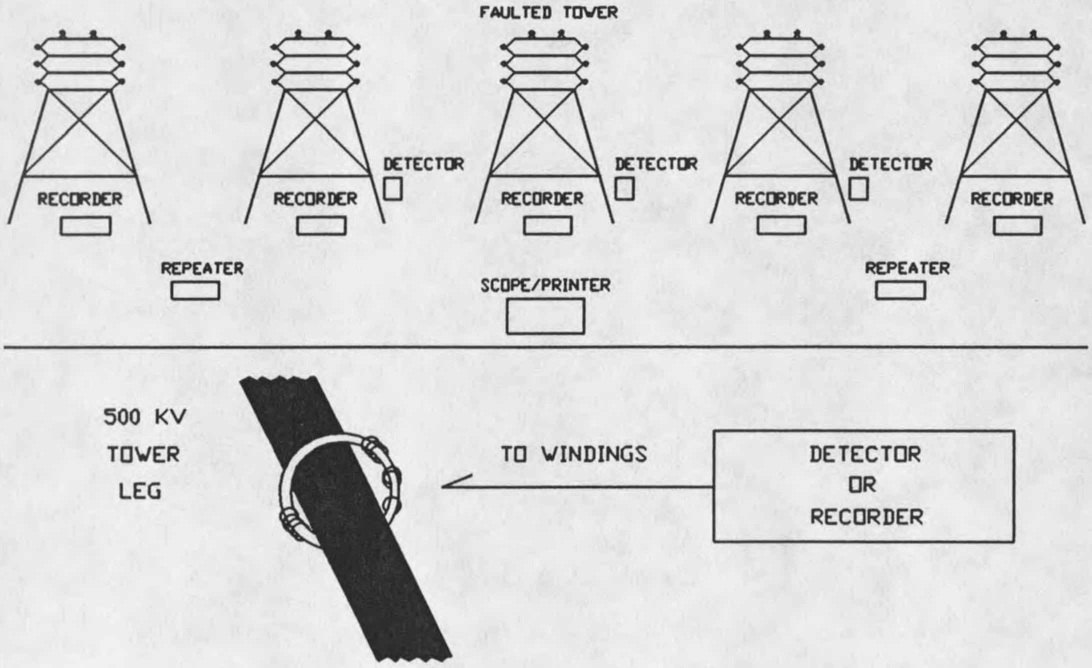


Figure 17. Proposed 500 KV Line Fault Test Equipment Configuration

Fault Test Equipment

Recorder. Five Digital Transient Fault Recorders, designated as FLS-03FD01, will be used for this test. All five Recorders will have the new differential amplifier configuration and will record the data generated by the four sensors. The Recorders will acquire data on five towers covering approximately a one mile span.

Scope. To eliminate the Recorder and scope interference a separate self contained analog circuit, designated as FLS-03SI01, will be built for the oscilloscope which will be located at the faulted tower.

Fault Detector. Three FLS-03FD01 Fault Detectors will be used to determine the location of the fault. This version of Fault Detectors have the differential amplifier configuration. The detection scheme is discussed in Software Based Fault Detection Logic section. It is important to note that only a software change is needed to change the detectors between a Type I Fault Detector and a Type II Fault Detector.

Repeater/Monitor. Two complete Repeater/Monitors will be used to receive and display the message frames transmitted by the Fault Detectors. Error correction and formatting of the received frame will be performed by the units. The Repeater/Monitors are capable of storing and recalling up to eight message frames from the Fault Detectors. A decision on the location of the faulted tower will be made based upon the information in the message frames from the Fault Detectors.

CHAPTER 6

CONCLUSIONS

A Power Transmission Line Fault Location System has been presented. The system detects and locates phase to ground and phase to phase faults to the nearest support tower of overhead power transmission lines. Fault Detectors are placed on each tower of the transmission line. When a fault occurs the Fault Detector at the faulted tower transmits a message frame containing the location of the fault. The message frame also contains the type of fault or values proportional to fault current magnitude. The message frames are relayed by repeaters to a control room where the message frames are displayed on a monitor. Control room personnel then dispatch linemen to the fault location to fix the problem. Error correction encoding is used to improve the reliability of the data in the received message frames.

In this thesis, transmission lines are classified according to the arrangement of the static wire. In Type I line configuration the static wire is grounded at each tower by a tower ground wire. Type II line configuration is a sectionalized line in which the static wire is divided into segments (typically six miles long) that are insulted from one another. The middle of each of these segments is grounded by a tower ground wire. The segment is insulated from all other towers. Type III line configuration consists of no static wire. Type I Fault Detectors are installed on Type I transmission lines while Type II Fault Detectors are installed on Type II and Type III transmission lines.

In Type I line configuration current flows away from the faulted tower through the static and tower ground wires during a phase to ground fault. Current flows through the non-faulted towers on the line. Sensors placed on the static wire sense the direction of fault current. During a phase to phase fault an air core sensor is used to detect the presence of flux from the shorting arc. The Fault Detector at the faulted tower transmits a message frame containing the type of fault and fault location.

In Type II and III line configurations current flows down the faulted tower into the ground during a phase to ground fault. Current sensors are placed around one leg on the tower structure to sense the magnitude of fault current down the tower. For Type II line configurations flash-over from the faulted tower to the insulated static wire may occur. If this happens more than one Fault Detector may be awakened. Each Fault Detector that is awakened transmits a message frame containing the magnitude of fault current down the tower and the tower's location. The tower with the greatest magnitude of current down the tower is the faulted tower.

The Fault Detectors detected and located faults in the laboratory and on 100 KV and 115 KV Type I configuration transmission lines. Three staged phase to ground faults on 100 KV and 115 KV transmission lines were detected correctly. The phase relationship between the sensors on the static wire were as expected. One out of two staged phase to phase faults on 100 KV and 115 KV transmission lines were detected correctly. The presence of flux from the shorting arc for the correctly detected fault was as expected. It was determined that transient noise during the first half cycle of the non-detected fault caused the Fault Detector at the faulted tower to malfunction.

Suggestions for future work on the Fault Location System involves:

1. Complete 500 KV Type II configuration transmission line fault test.
2. Design Fault Detectors which can be interrogated for system diagnostic purposes.
3. Integrate the Fault Location System in a power company's communications system.
4. Design software for the Fault Location System which locates faults to within one mile spans instead of one supporting tower. A Fault Detector will not be needed at each tower thus improving the cost effectiveness of the system.

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REFERENCES

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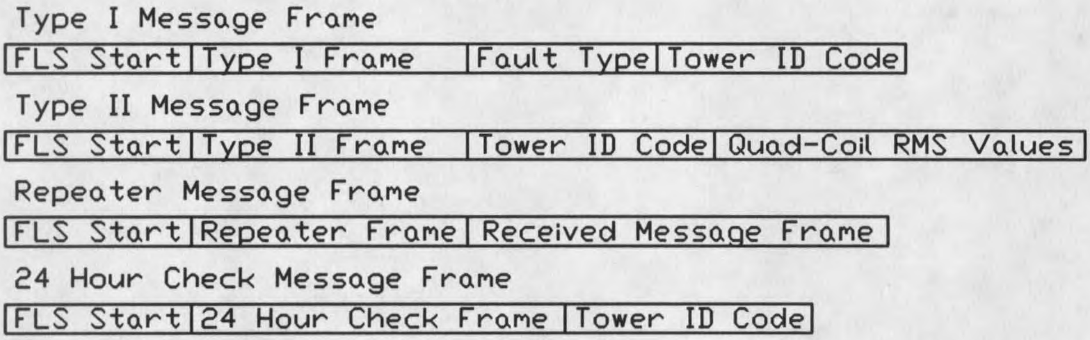
APPENDICES

APPENDIX A

COMMUNICATIONS

Message Frames

There are 4 message frame types specified for the system (Figure 18). The first byte identifies the frame as a Fault Location System (FLS) message frame. The next byte identifies the source of the frame (e.g. from Type I Fault Detector, from Type II Fault Detector, ...). The data for the frame are contained in the remaining bytes.



Type I Message Frame

FLS Start	Type I Frame	Fault Type	Tower ID Code

Type II Message Frame

FLS Start	Type II Frame	Tower ID Code	Quad-Coil RMS Values

Repeater Message Frame

FLS Start	Repeater Frame	Received Message Frame

24 Hour Check Message Frame

FLS Start	24 Hour Check Frame	Tower ID Code

Figure 18. Fault Location System Message Frames

Error-Correcting Code

Message frames are encoded using a (7,4) Hamming code (Table 4). The seven bit codewords consists of a data-nibble (i.e. four data bits) and three parity bits. A systematic code was chosen since data are easily identified within the codeword; the last four bits of the codeword are the same as the data-nibble.

The construction of the code used is as follows. First, the parity check matrix **H** is chosen with the first three columns containing an identity matrix making the code systematic.

$$\boldsymbol{H} = [\boldsymbol{I} \vdots \boldsymbol{P}] = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 0 & 1 \end{bmatrix}$$

Next, the generator matrix is defined.

$$\boldsymbol{G} = [\boldsymbol{P}^T \vdots \boldsymbol{I}] = \begin{bmatrix} 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The codewords are then generated by the vector-matrix product

$$\boldsymbol{c} = \boldsymbol{aG}$$

where **a** is the four bit data-nibble and **c** is the resulting seven bit codeword. The sixteen possible data-nibbles and their resulting codewords are shown in Table 4. This table, stored as a look-up table in software, is used to encode the data. To transmit an eight bit byte an additional filler bit is added to the codeword.

The decoder operates as follows. The received word **r** has components

$$\boldsymbol{r} = \boldsymbol{c} + \boldsymbol{e}$$

where **c** is the uncorrupted codeword and **e** is the error vector. To isolate the error vector the parity check matrix and the received word are multiplied

$$\begin{aligned} \boldsymbol{s} &= \boldsymbol{Hr} \\ &= \boldsymbol{HG^{T}a^{T}} + \boldsymbol{He^{T}} \\ &= \boldsymbol{He^{T}} \end{aligned}$$

since

$$\begin{aligned} \boldsymbol{HG^{T}} &= [\boldsymbol{IP}]\begin{bmatrix} \boldsymbol{P} \\ \boldsymbol{I} \end{bmatrix} \\ &= \boldsymbol{P} + \boldsymbol{P} = \mathbf{0} \end{aligned}$$

The syndrome, **s**, is equal to zero if there is no error. If there is an error, the syndrome is equal to a column of the parity check matrix H. This column corresponds to the position of the error bit. The error bit is corrected by reversing its binary value (i.e. 0 to 1 or 1 to 0). One bit error per codeword can be corrected since the minimum distance between codewords is three. If the codeword has more than one bit in error the codeword will be decoded incorrectly.

Table 4. (7,4) Hamming Code

Binary		Hexadecimal	
Dataword	Codeword	Dataword	Codeword
0 0 0 0	0 0 0 0 0 0 0	0	00
0 0 0 1	1 1 1 0 0 0 1	1	71
0 0 1 0	1 1 0 0 0 1 0	2	62
0 0 1 1	0 0 1 0 0 1 1	3	13
0 1 0 0	1 0 1 0 1 0 0	4	54
0 1 0 1	0 1 0 0 1 0 1	5	25
0 1 1 0	0 1 1 0 1 1 0	6	36
0 1 1 1	1 0 0 0 1 1 1	7	47
1 0 0 0	0 1 1 1 0 0 0	8	38
1 0 0 1	1 0 0 1 0 0 1	9	49
1 0 1 0	1 0 1 1 0 1 0	A	5A
1 0 1 1	0 1 0 1 0 1 1	B	2B
1 1 0 0	1 1 0 1 1 0 0	C	6C
1 1 0 1	0 0 1 1 1 0 1	D	1D
1 1 1 0	0 0 0 1 1 1 0	E	0E
1 1 1 1	1 1 1 1 1 1 1	F	7F

APPENDIX B

STATISTICAL RESULTS

Table 5. Statistical Results For Phase To Ground Faults At Montana State University

Fault	Location	This Tower	FTYPE	VALID SAMPLES	OUT OF PHASE	Decision
11-29G	Ryon Lab	Yes	0B	0F	0F	Correct
11-29H	Ryon Lab	Yes	0B	0F	0F	Correct
11-29L	Field	Yes	16	00	00	WRONG(1)
12-1A	Field	Yes	0B	08	06	Correct
12-1B	Field	Yes	0B	06	06	Correct
12-1C	Field	Yes	16	04	04	WRONG(2)
12-4A	Field	Yes	0B	05	05	Correct(3)
12-4B	Field	Yes	0B	0B	09	Correct(3)
12-4C	Field	Yes	0B	08	06	Correct(3)
12-10A	Field	Yes	0B	09	07	Correct
12-10B	Field	Yes	0B	09	07	Correct
11-29I	Ryon Lab	No	00	10	00	Correct
11-29J	Ryon Lab	No	00	10	01	Correct
12-1G	Field	No	00	10	00	Correct
12-1H	Field	No	00	0F	00	Correct
12-1I	Field	No	00	10	00	Correct
12-4D	Field	No	00	10	00	Correct
12-10C	Field	No	00	10	01	Correct

(1) Before additional ground rods, current through one coil is low.

(2) Just under number of Valid Samples, current through coil B is low, note faults 12-1A and 12-1B.

(3) Gain on coil B was increased to 21 for fault 12-4A and further increased to 41 for all subsequent faults.

Note: The fault numbering system consists of a date and a fault Number. Example: 11-29I is the Ith fault on November 29.

Table 6. Statistical Results For Phase To Phase Faults At Montana State University

Fault	Location	This Tower	FTYPE	VALID SAMPLES	OUT OF PHASE	Decision
11-29A	Ryon Lab	Yes	16	00	00	Correct
11-29B	Ryon Lab	Yes	16	00	00	Correct
11-29C	Ryon Lab	Yes	16	00	00	Correct
11-29D	Ryon Lab	Yes	0B	07	07	WRONG(1)
11-29E	Ryon Lab	Yes	16	00	00	Correct
11-29F	Ryon Lab	Yes	16	00	00	Correct
11-29L	Field	Yes	16	00	00	Correct
12-1D	Field	Yes	16	00	00	Correct
12-1E	Field	Yes	16	00	00	Correct
12-1F	Field	Yes	16	00	00	Correct
12-4E	Field	Yes	16	03	00	Correct
12-10D	Field	Yes	16	01	01	Correct
12-1J	Field	No	--	--	--	Correct(2)
12-1K	Field	No	--	--	--	Correct(2)
12-10E	Field	No	--	--	--	Correct(2)

(1) Coils 4" from pole, sparking effects coils on static wire.

(2) Unit should not trigger, therefore no data is stored.

Table 7. Fault Detector Data For Fault Tests At Montana State University

Date: May 15, 1991
Location: Huffman Field Model Power Line

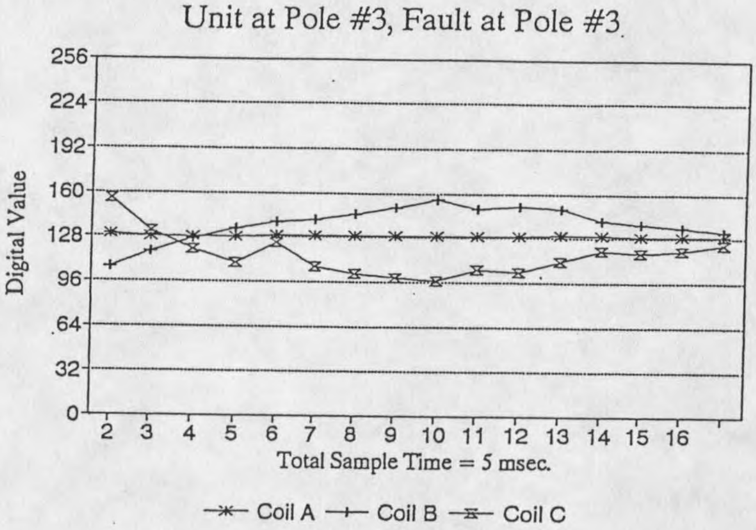
Type of Fault	Fault at Pole Number	Detection Unit Data				
		Pole Number	Fault Type	Out of Phase	Valid Samples	Valid_C
Phase 1 to Ground	2	2	F1	38	38	E
	2	2	F1	39	39	D
	3	3	F1	35	35	16
	3	3	F1	37	37	17
Phase 2 to Ground	2	2	F1	37	37	D
	2	2	F1	37	37	B
	3	3	F1	36	36	15
	3	3	F1	33	33	E
	4	4	F1	36	36	2D
	4	4	F1	36	36	2F
Phase 1 to Phase 2	2	2	F2	0	0	12
	2	2	F2	0	0	29
	3	3	F2	0	0	12
	3	3	F2	0	0	14

NOTES:
F1 = Phase to Ground Fault
F2 = Phase to Phase Fault
All data in Hex

APPENDIX C

FAULT WAVEFORMS

<u>Montana State University</u>



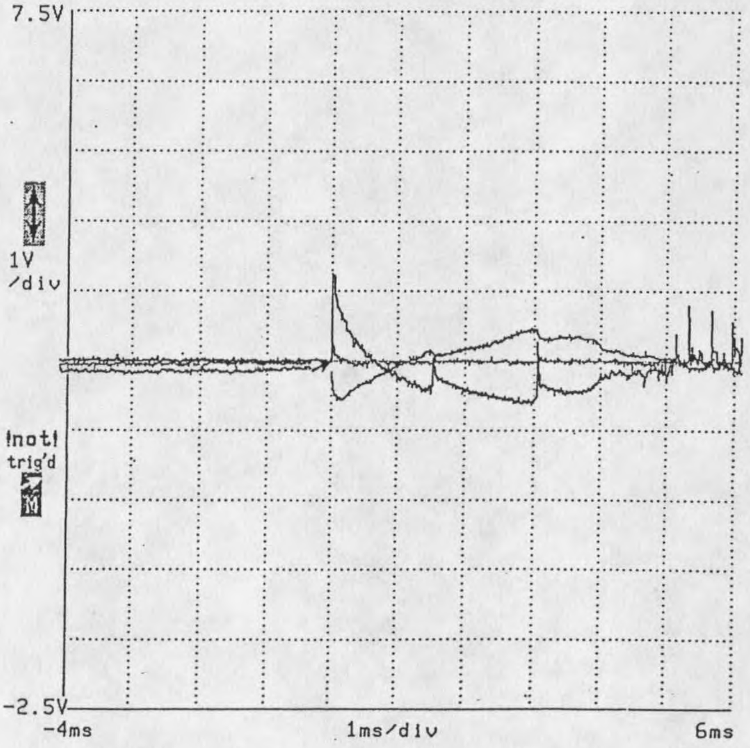


Figure 19. Phase To Phase Fault (#11-29F) At Montana State University

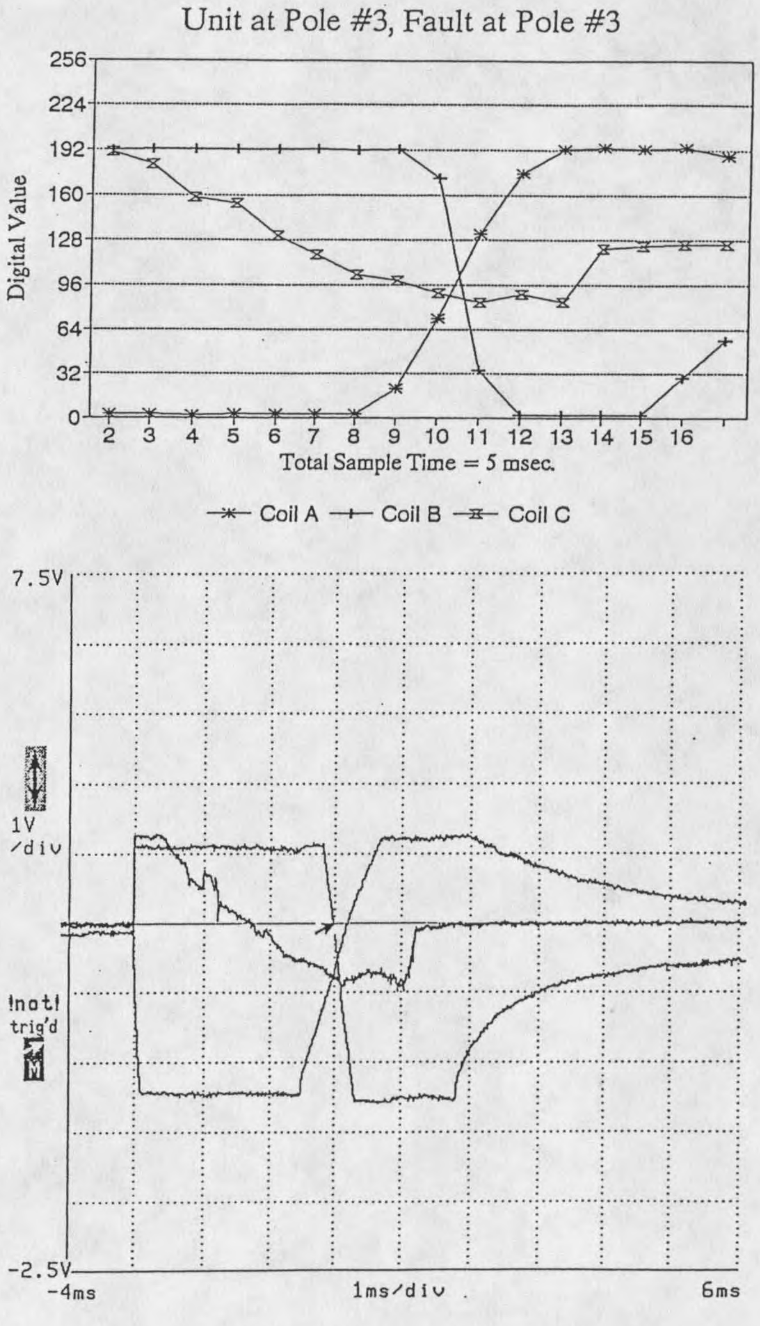


Figure 20. Phase To Ground Fault (#11-29G) At Montana State University

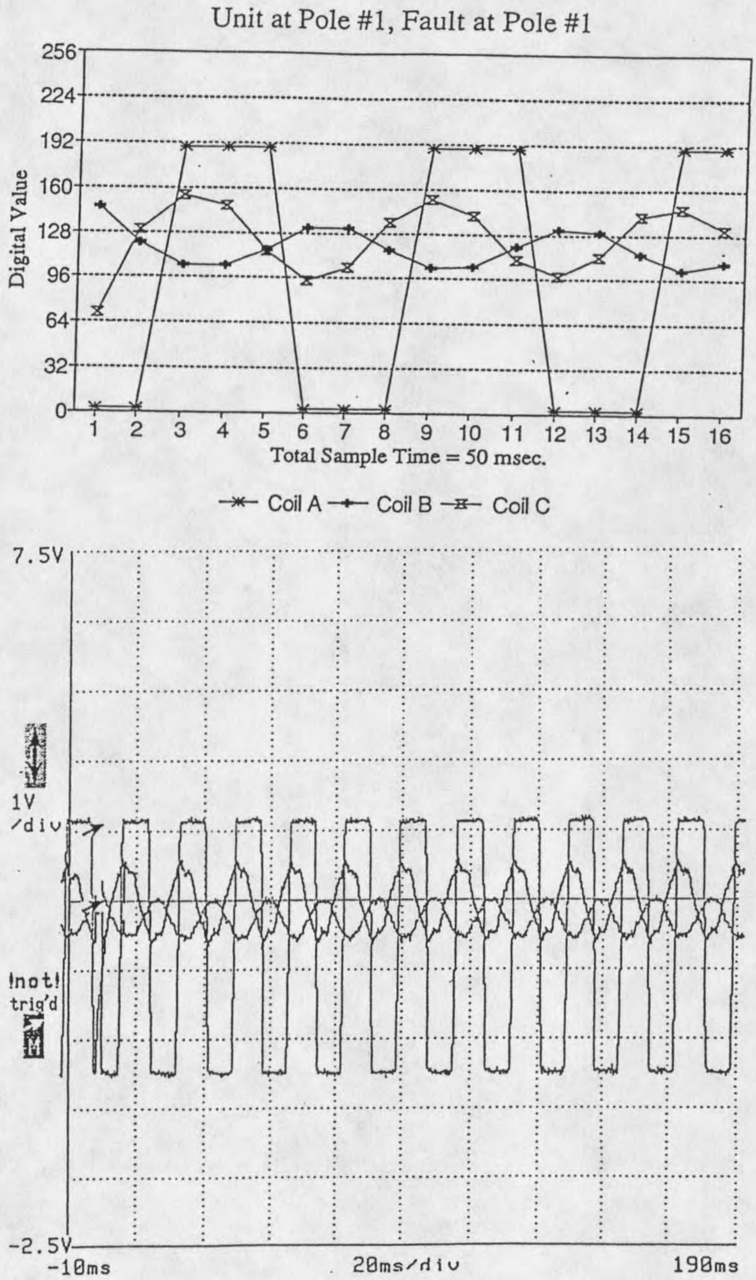


Figure 21. Phase To Ground Fault (#12-4B) At Montana State University

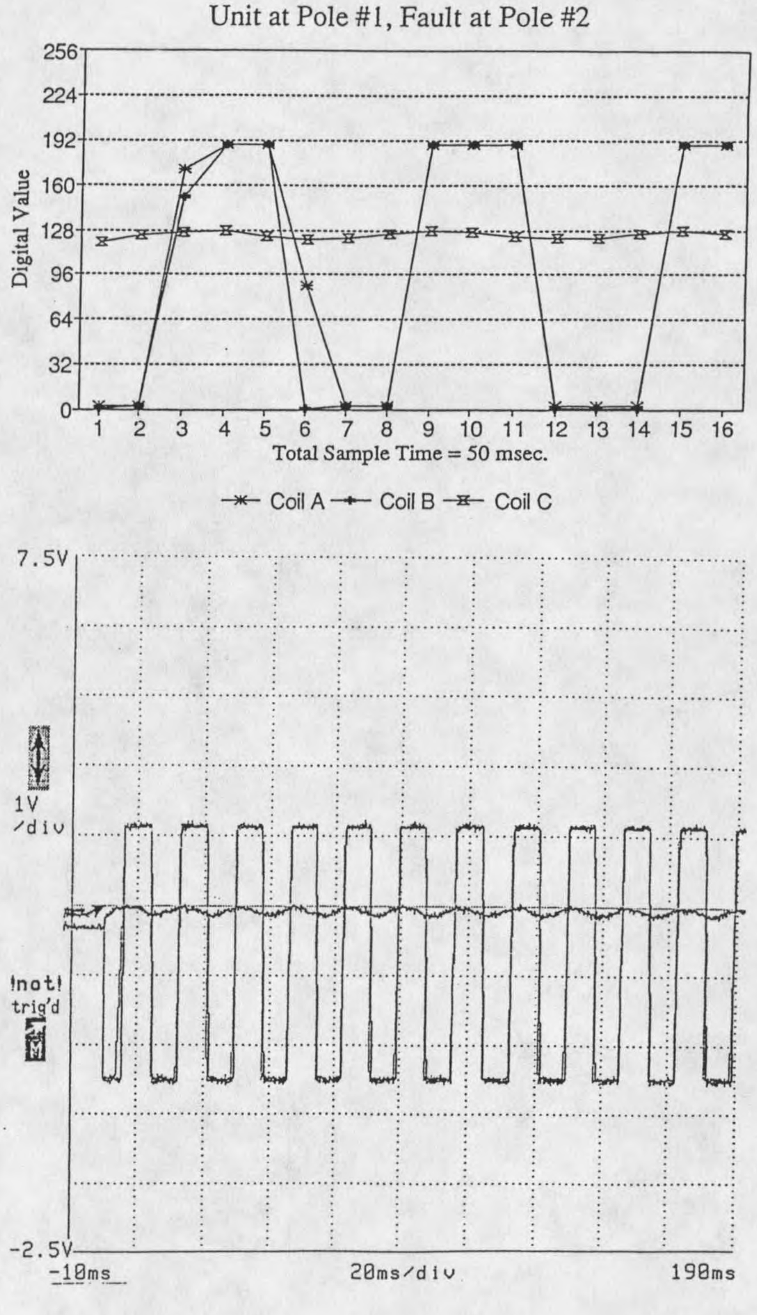


Figure 22. Phase To Ground Fault (#12-4D) At Montana State University

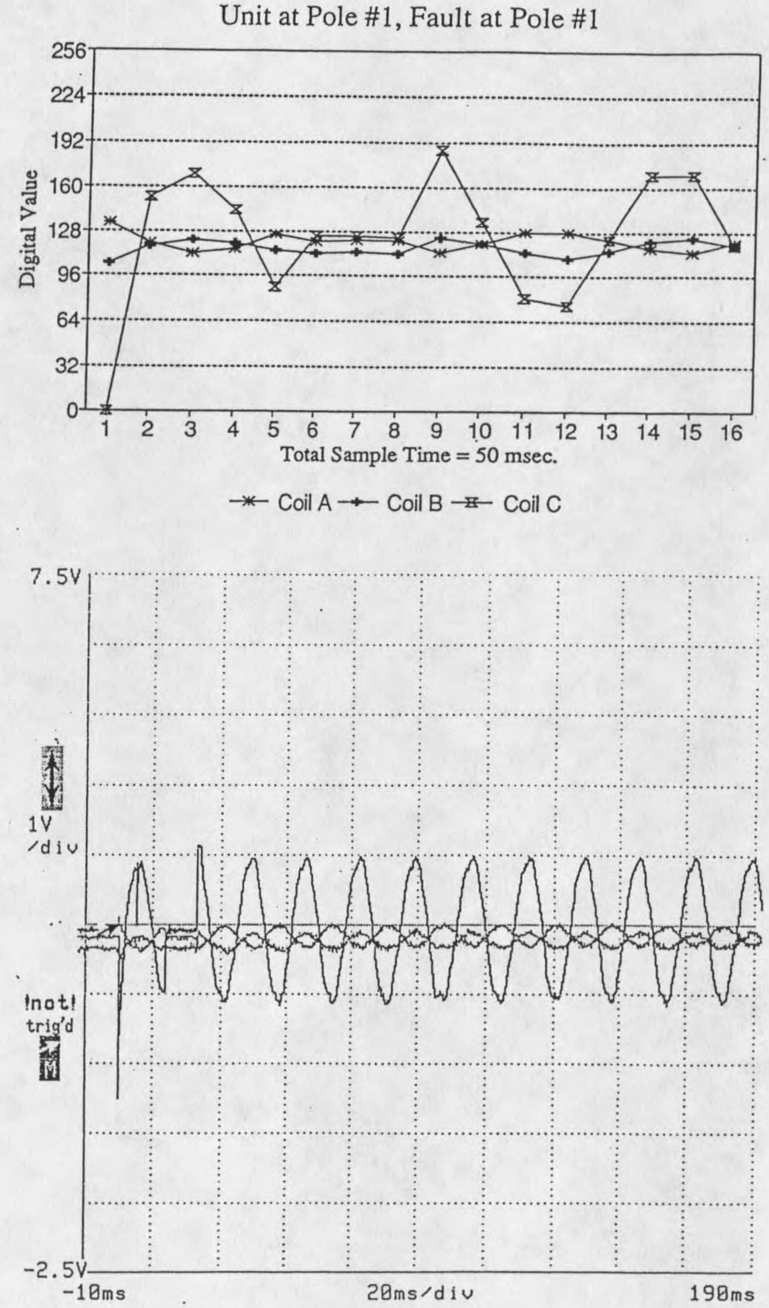
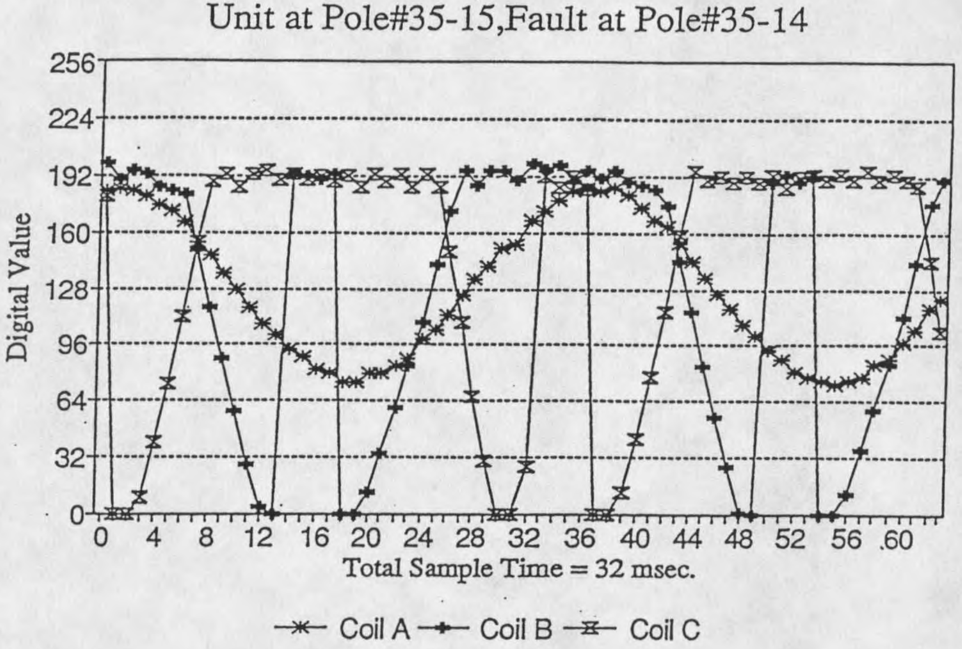


Figure 23. Phase To Phase Fault (#12-4E) At Montana State University

Conrad Auto


Unit at Pole#35-15,Fault at Pole#35-14

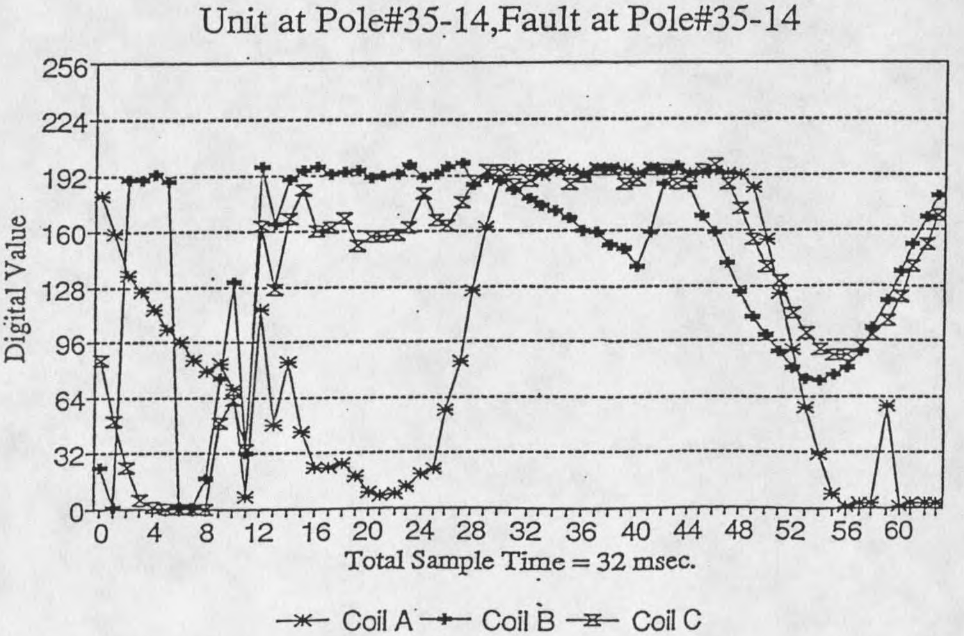

Unit at Pole#35-14,Fault at Pole#35-14

Figure 24. Phase To Ground Fault At Conrad Auto

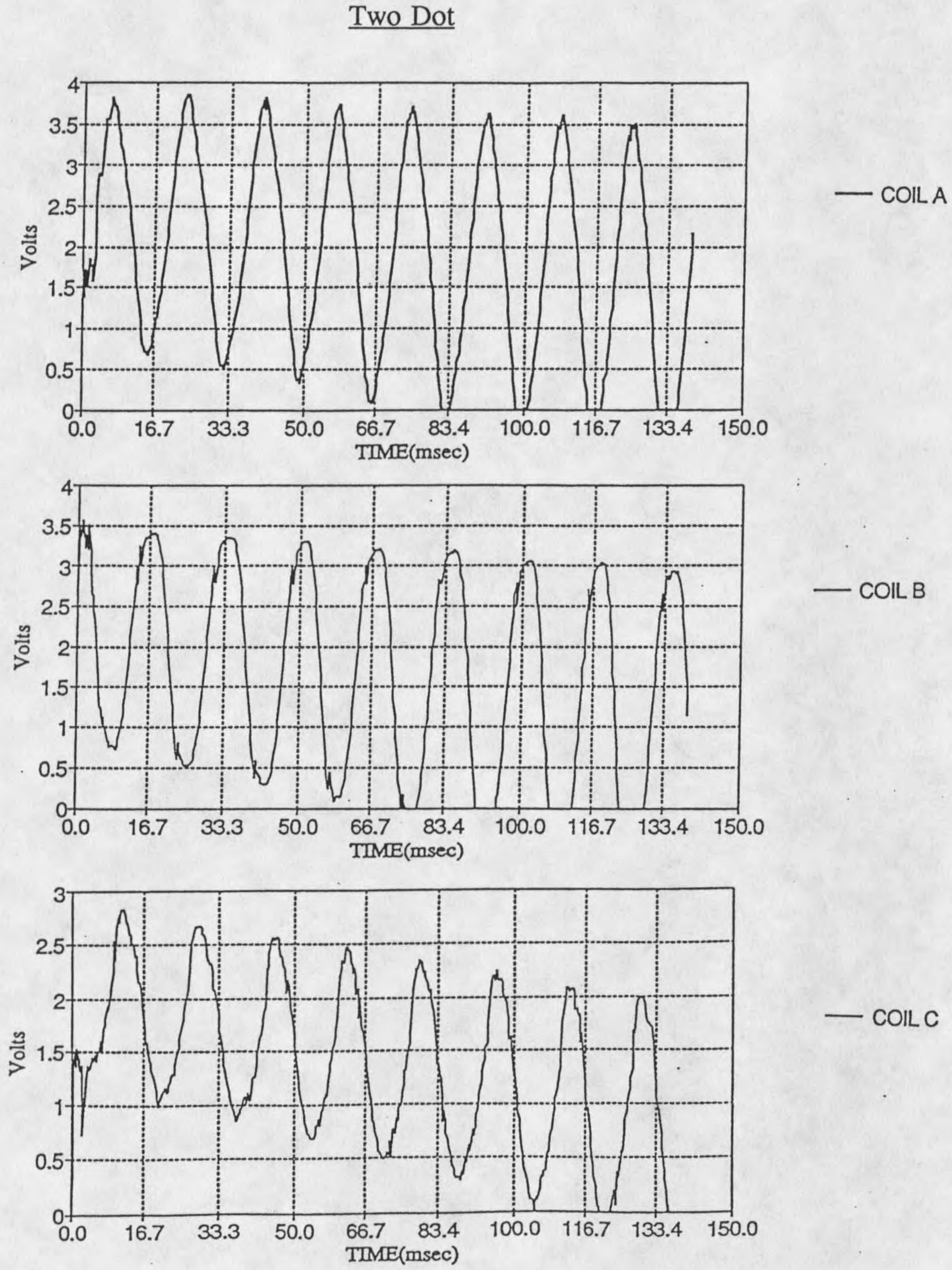


Figure 25. First Phase To Ground Fault At Two Dot (Recorder B)

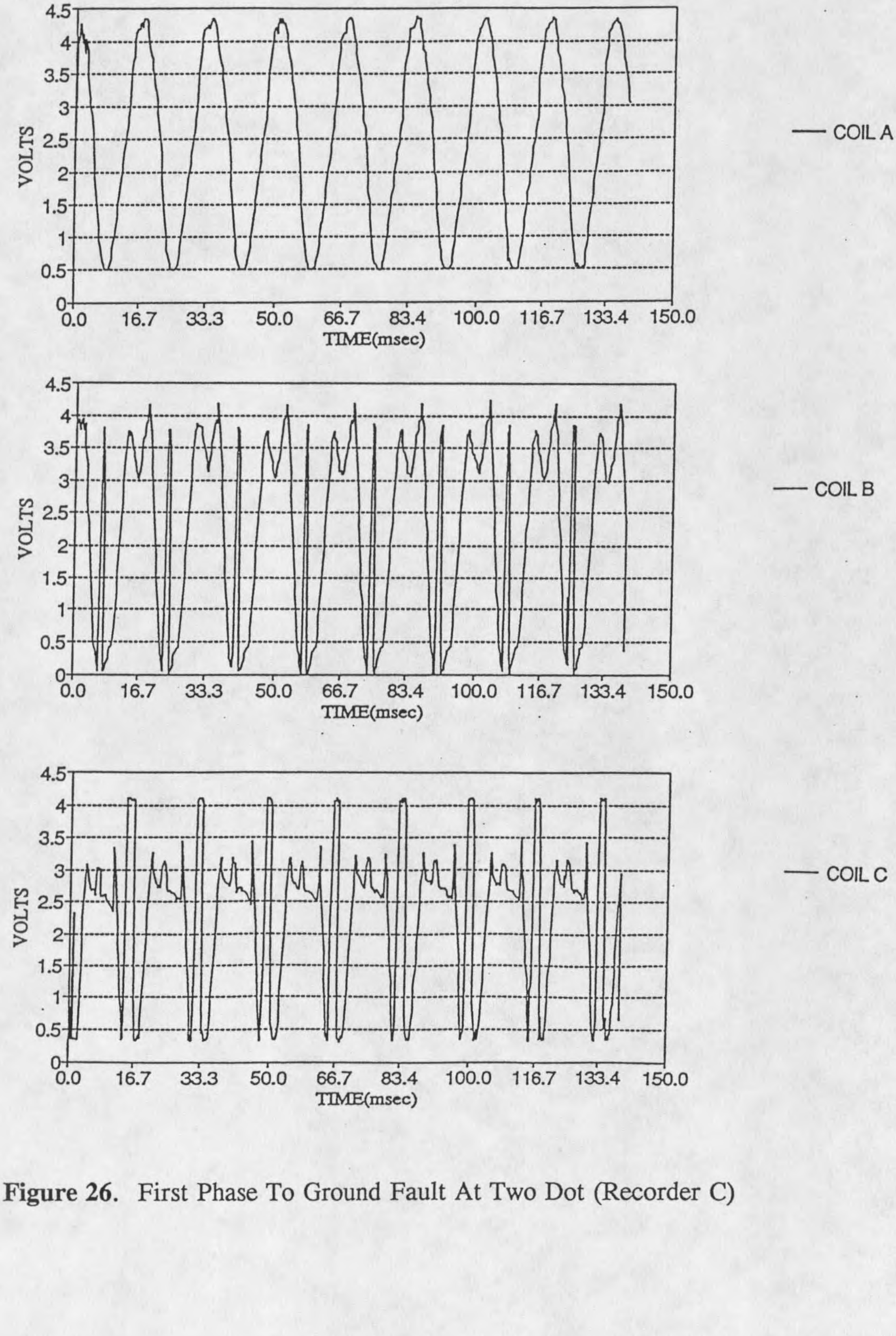


Figure 26. First Phase To Ground Fault At Two Dot (Recorder C)

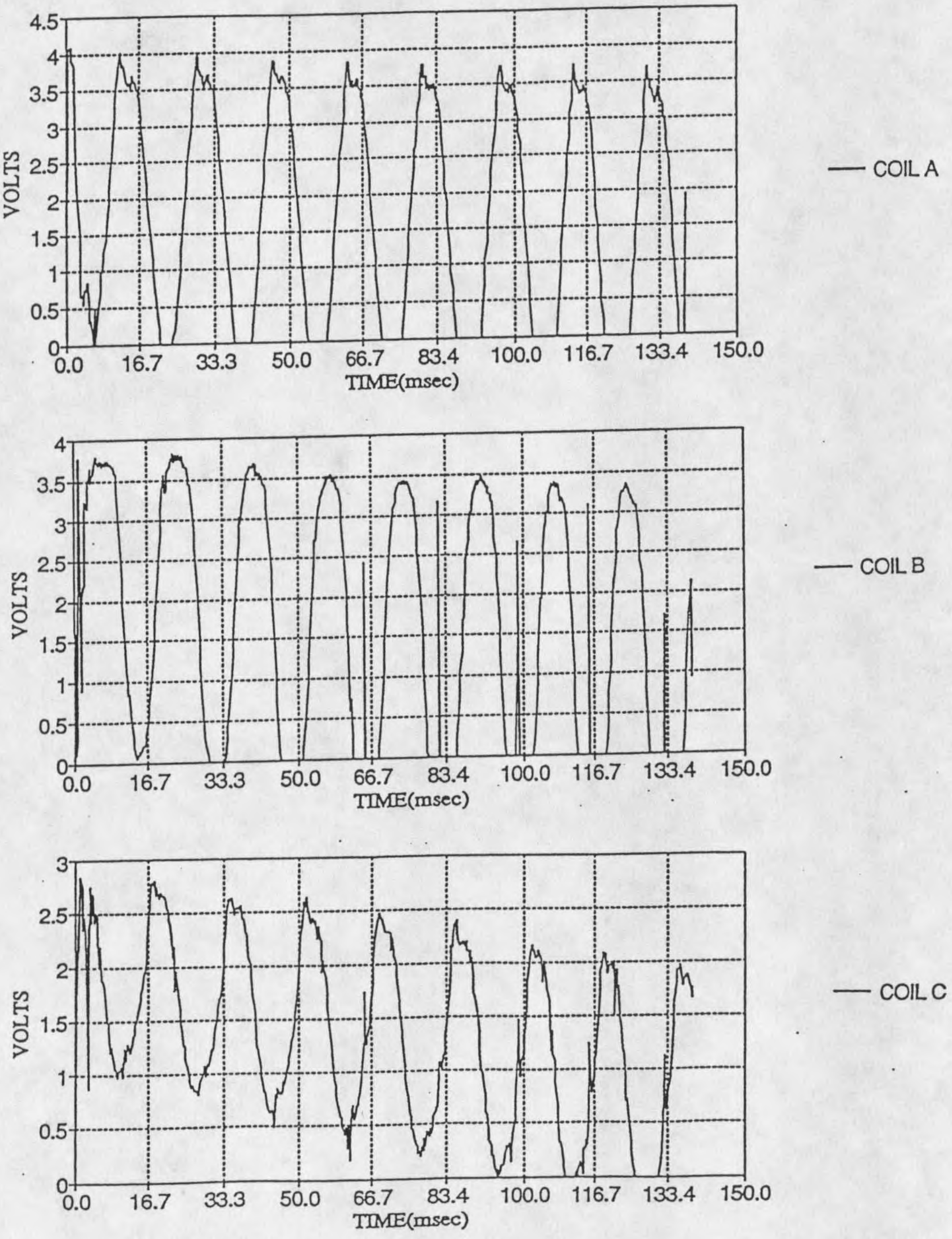


Figure 27. Second Phase To Ground Fault At Two Dot (Recorder B)

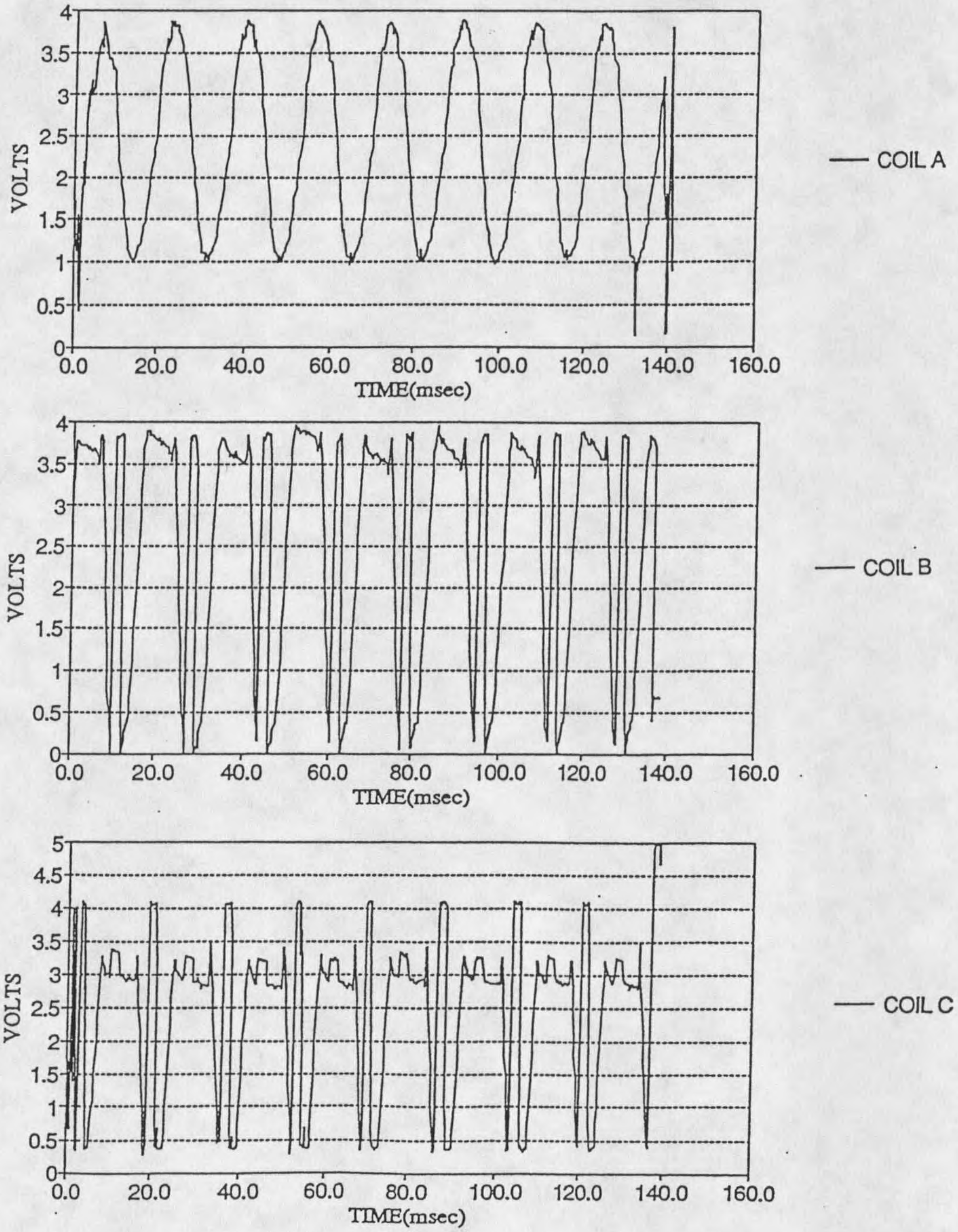


Figure 28. Second Phase To Ground Fault At Two Dot (Recorder C)

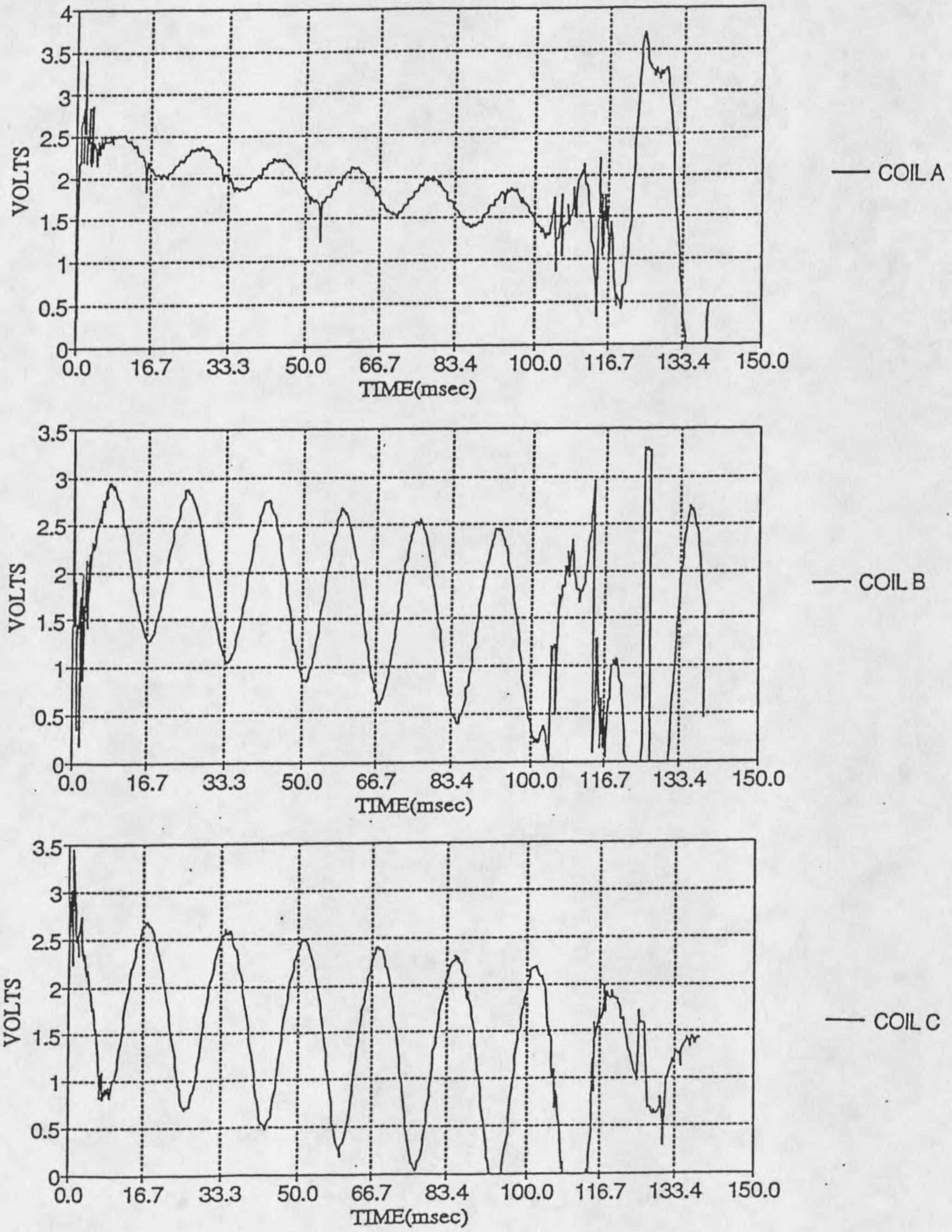


Figure 29. Phase To Phase Fault At Two Dot (Recorder B)

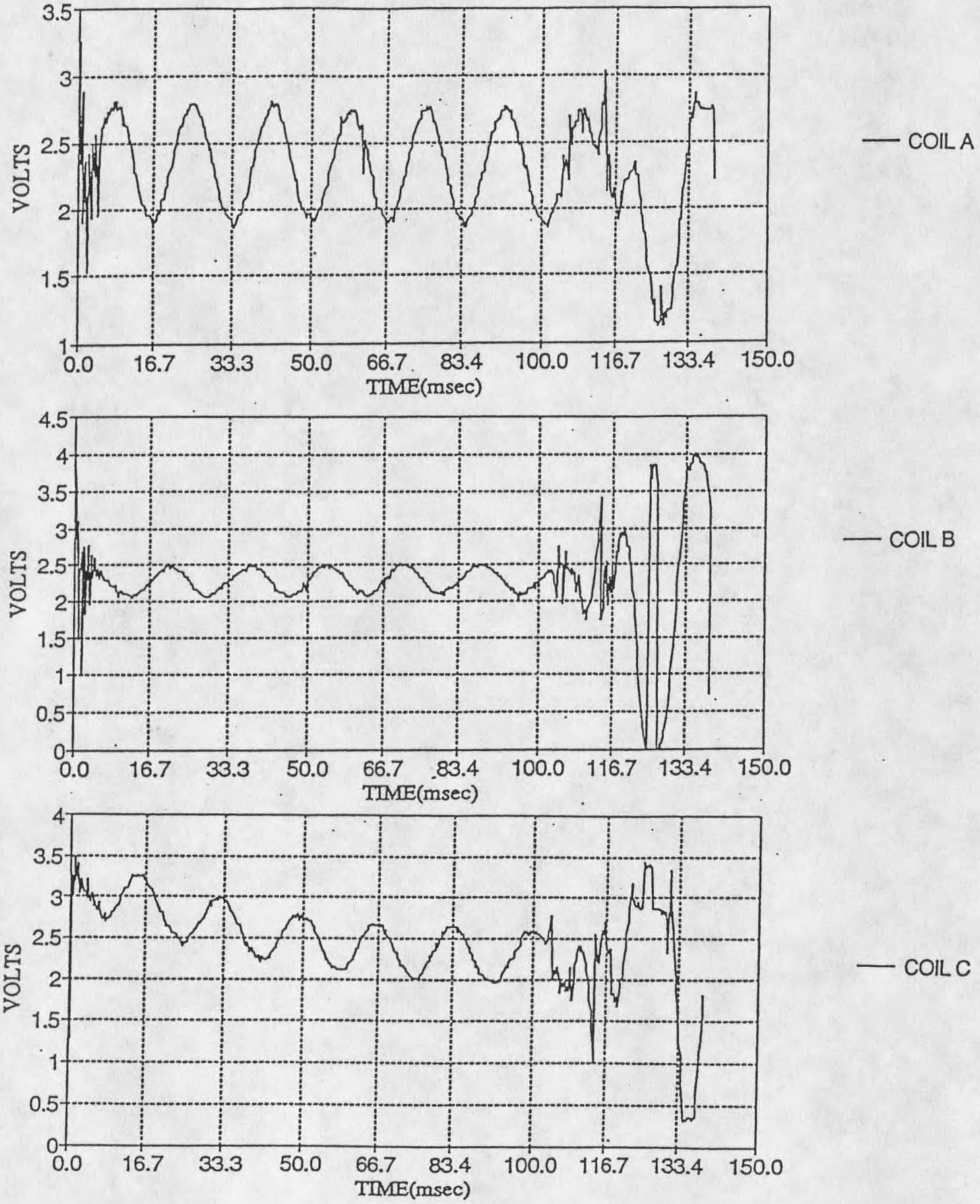


Figure 30. Phase To Phase Fault At Two Dot (Recorder C)

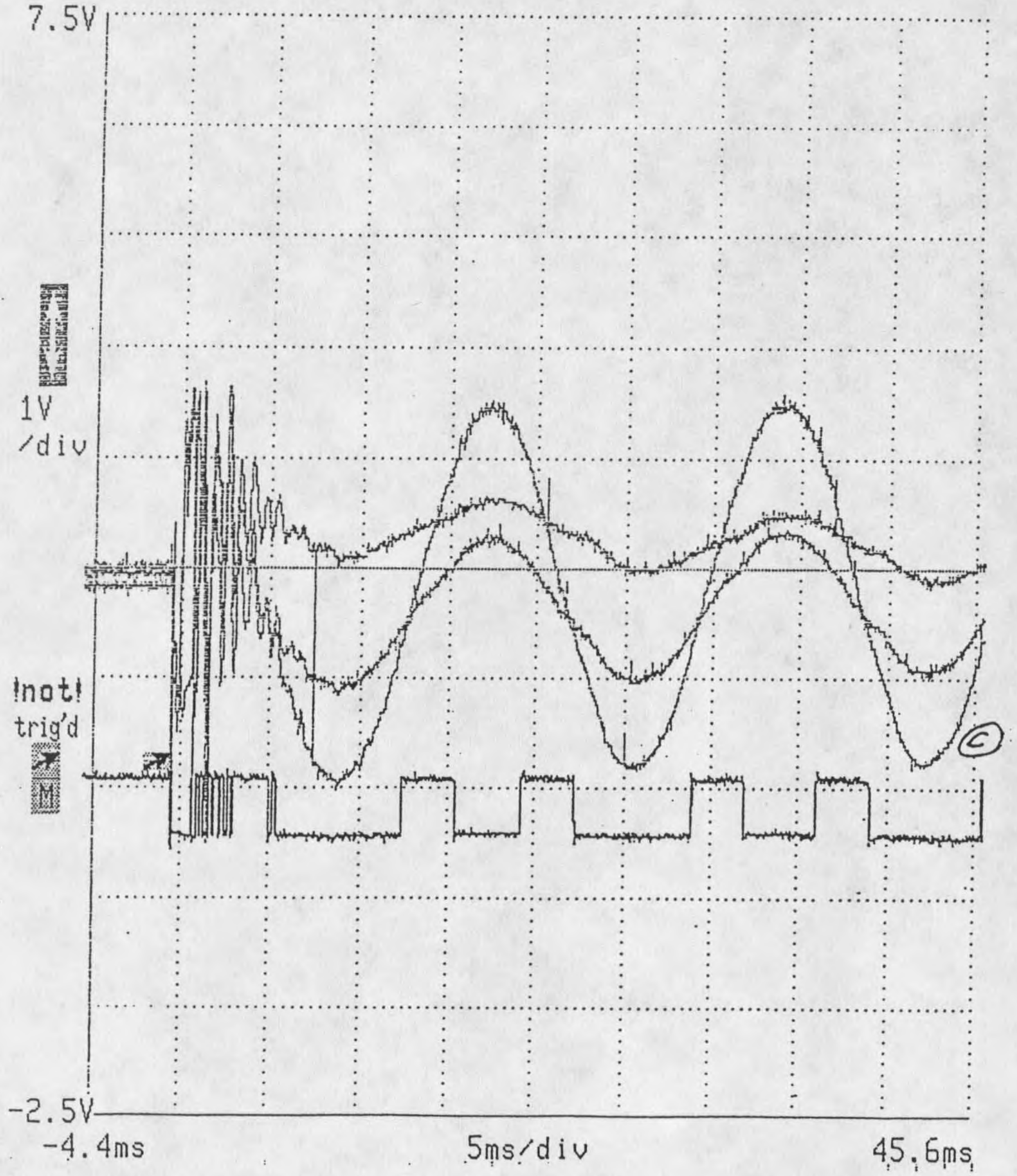


Figure 31. Phase To Phase Fault At Two Dot (Oscilloscope)